PB89-229843

Feasibility and Cost-Effectiveness of Controlling Emissions from Diesel Engines in Rail, Marine Construction, Farm, and Other Mobile Off-Highway Equipment

Radian Corp., Sacramento, CA

Prepared for:

Environmental Protection Agency, Washington, DC

Feb 88

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO. PB89 229843/AS
4. TITLE AND SUBTITLE Feasibility and Cost Effectivness of Controlling Emissions from Diesel Engines In Rail, Marine, Construction, Farm, and Other Off-Highway Equipment.		5. REPORT DATE February 1988
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Christopher S. Weaver		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Radian Corporation 10395 Old Placerville Road Sacramento, CA 95827		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. EPA 68-01-7288 Work Assignment 5
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Office of Policy Analysis 401 M. Street S.W. Washington, D.C. 20460		13. TYPE OF REPORT AND PERIOD COVERED Final Report
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Diesel engines in off-highway vehicles and other off-highway mobile equipment, while less numerous than those in highway trucks and buses, are still significant contributors to oxides of nitrogen (NOx) and particulate inventories in many urban areas. These engines are presently exempt from any emissions control requirements. Consequently, they produce far more pollution (per unit of fuel input or work output) than the otherwise similar emission-controlled engines used in on-highway vehicles. The recent promulgation of stringent NOx and particulate emission standards for diesel engines in on-highway vehicles has drawn attention to diesel emissions in general, and has raised the question of whether similar emissions standards might be appropriate for off-highway diesel engines.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air pollution Automobiles Buses (vehicles) Diesel engines Exhaust emissions Nitrogen oxides Trucks	Marine Engines Cost Effectiveness Agricultral machinery Construction equipment Railroad trains	Mobile refrigerations Particulate emissions Federal regulations	

18. DISTRIBUTION STATEMENT Release Unlimited	19. SECURITY CLASS *(This Report)* unclassified	21. NO. OF PAGES 146
	20. SECURITY CLASS *(This page)* unclassified	22. PRICE

EPA Form 2220-1 (9-73)

EXECUTIVE SUMMARY

Diesel engines in off-highway vehicles and other off-highway mobile equipment, while less numerous than those in highway trucks and buses, are still significant contributors to NO_x and particulate inventories in many urban areas. These engines are presently exempt from any emissions control requirements. Consequently, they produce far more pollution (per unit of fuel input or work output) than the otherwise similar emission-controlled engines used in on-highway vehicles. The recent promulgation of stringent NO_x and particulate emissions standards for diesel engines in on-highway vehicles has drawn attention to diesel emissions in general, and has raised the question of whether similar emissions standards might not be appropriate for off-highway diesel engines.

Background

Emissions from diesel engines used in on-highway trucks and buses have been regulated with increasing stringency since 1972. New Federal regulations adopted in 1985 will limit particulate matter (PM) emissions from heavy-duty diesel engines to 0.6 grams per brake horsepower-hour (g/BHP-hr), beginning in the 1988 model year. The NO_x emissions limit, currently at 10.7 g/BHP-hr, will be reduced to 6.0 g/BHP-hr in 1990, and to 5.0 g/BHP-hr in 1991. A new PM limit of 0.25 g/BHP-hr (0.1 g/BHP-hr for buses) is also scheduled for 1991, and a PM limit of 0.1 g/BHP-hr for all vehicles is scheduled for 1994.

Although they are technically very similar to on-highway diesel engines, engines used in off-highway mobile equipment such as locomotives, farm and construction equipment, boats, and similar applications are presently exempt from any emissions controls. The Clean Air Act gives EPA authority to regulate "stationary sources" of emissions, and "motor vehicles", but the term "motor vehicle" has traditionally been interpreted to include on-highway vehicles only. Since off-highway mobile sources are neither "stationary" nor "motor vehicles", EPA appears to have no authority to regulate them. If regulations were considered desirable, Congressional action would be needed to provide the required authority.

Scope of This Report

Radian Corporation was commissioned by the U.S. EPA, Office of Policy Analysis to study the feasibility and cost-effectiveness of emissions controls in off-highway diesel vehicles. This document is the final report of that study. This report addresses the following major categories of diesel-engined off-highway equipment:

- Railroad locomotives;
- Marine vessels (except large oceangoing ships);
- Farm equipment;
- Construction and industrial equipment (including mining and forestry equipment); and
- Mobile Refrigeration Units.

These categories include the most significant classes of mobile diesel engines except for on-highway vehicles (which are already regulated) and oceangoing motorships.

Results and Conclusions

Based on the estimates developed for this report, total pollutant emissions from off-highway diesel engines are large both in absolute terms and in proportion to their total numbers, power output, and fuel consumption. Table E-1 summarizes the estimated population, annual fuel consumption, and emissions for the five classes of off-highway diesel engines considered in this report. Estimated pollutant emissions are reported both in tons per year and as a percentage of the estimated total emissions of that pollutant by all sources nationwide. Off-highway diesel engines are estimated to produce about

TABLE E-1. ESTIMATED NATIONWIDE POPULATION AND EMISSIONS FROM DIESEL ENGINES USED IN OFF-HIGHWAY APPLICATIONS

	No. of Engines	Total Horsepower (1,000s)	Fuel Consumption (1,000 gal)	Emissions (tons/yr)			
				HC	CO	NO_x	PM
Locomotives							
Medium Speed	26,105	61,111	3,409,476	30,999	308,558	901,645	37,041
Percent of Nationwide[1]				0.13%	0.40%	4.16%	0.48%
Marine Vessels							
High Speed	438,000	45,471	915,671	14,651	54,482	199,616	10,988
Medium Speed	5,000	11,173	917,607	18,811	85,796	244,542	9,176
Total	443,000	56,644	1,833,278	33,462	140,278	444,158	20,164
Percent of Nationwide				0.14%	0.18%	2.05%	0.26%
Farm Equipment							
High Speed	3,868,019	332,139	3,021,561	108,603	274,669	688,874	75,103
Percent of Nationwide				0.46%	0.36%	3.17%	0.97%
Construction and Industrial Equipment							
High Speed	1,047,805	124,056	3,279,661	47,820	191,064	590,372	50,021
Percent of Nationwide				0.20%	0.25%	2.72%	0.65%
Mobile Refrigeration							
High Speed	203,000	9,518	494,167	10,921	44,347	115,520	4,991
Percent of Nationwide				0.05%	0.06%	0.53%	0.06%
TOTALS							
High Speed	5,556,824	511,184	7,711,060	181,995	564,562	1,594,382	141,103
Medium Speed	31,105	72,284	4,327,083	49,810	394,354	1,146,187	46,217
Total	5,587,929	583,468	12,038,143	231,805	958,916	2,740,569	187,320
Percent of Nationwide				0.98%	1.25%	12.63%	2.43%

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[1] Percent of nationwide emissions inventory for that pollutant based on EPA (1986).

2.75 million tons of NO_x per year, 187,000 tons of particulate matter, 232,000 tons of unburned HC, and 959,000 tons of CO. These values are about 12.6 percent, 2.4 percent, one percent, and 1.25 percent, respectively, of estimated nationwide emissions of these pollutants from all sources (EPA, 1986).

More significant than the off-highway diesel contribution to the total emissions inventory is the off-highway contribution to the total for all mobile diesel engines, both on and off-highway. Table E-2 shows this calculation. As this table indicates, off-highway diesel engines are responsible for a disproportionate fraction of the total: accounting for 56 percent of the NO_x emissions, 57 percent of CO emissions, and 48 percent of HC emissions from mobile diesel engines, but only 41 percent of the diesel fuel burned. Their contribution to PM emissions is less than proportionate, however, at 36.5 percent of the total. Due to limited data, the numbers in Table E-2 are somewhat crude, but the conclusion is inescapable: off-highway diesel engines are currently an important source of emissions, comparable in magnitude to on-highway diesels.

Diesel engines in on-highway vehicles have been subject to emission regulations for many years, and have recently received a great deal of regulatory attention, which will lead to still lower emissions in the future. Off-highway engines, since they do not fall under EPA's statutory authority, have not been regulated. For this reason, pollutant emissions per unit of work produced or fuel consumed by an average off-highway diesel are much higher than those for an on-highway engine, and the potential for future reductions in emissions is correspondingly greater.

As described in greater detail in Sections Three through Eight of this report, emission control technology for on-highway diesel engines is well developed, and this technology could readily be transferred to most off-highway engines. Off-highway diesel engines can be divided into high-speed and medium-speed classes, having rated operating speeds above or below 1300

TABLE E-2. COMPARISON OF NATIONWIDE FUEL CONSUMPTION AND EMISSIONS OFF-HIGHWAY VS. ON-HIGHWAY DIESELS

	Fuel Consumption (1,000 gal)	Emissions (tons/yr)			
		HC	CO	NO_x	PM
Off-Highway Diesels (mid-1980s)[1]					
Locomotives	3,409,476	30,999	308,558	901,645	37,041
Marine Vessels	1,833,278	33,462	140,278	444,158	20,164
Farm Equipment	3,021,561	108,603	274,669	688,874	75,103
Const./Ind. Equipt.	3,279,661	47,820	191,064	590,372	50,021
Mobile Refrigeration	494,167	10,921	44,347	115,520	4,991
Total Off-Highway	12,038,143	231,805	958,916	2,740,569	187,320
On-Highway-Diesels (calendar 1984)[2]					
Heavy-Duty Vehicles	NA	242,290	693,832	2,136,563	297,357
Light-Duty Vehicles	NA	8,820	28,634	44,052	28,634
Total On-Highway	17,279,650	251,110	722,466	2,180,615	325,991
Total: All Mobile Diesel Engines	29,317,793	482,915	1,681,382	4,921,184	513,311
Off-Highway as Percent of All Mobile Diesels	41.1%	48.0%	57.0%	55.7%	36.5%

[1] Source: Radian estimates.

[2] Source: EPA (1986).

RPM, respectively. Except for railway locomotives, the great majority of off-highway diesel engines are high-speed types. These share many design features with on-highway truck and light-duty vehicle engines, so that most emissions control technologies demonstrated in on-highway engines would be readily transferable. Medium-speed engines are used in railway locomotives and some marine vessels. Emissions control technology for these engines is less developed, but even the little work that has been done shows the potential for major reductions in emissions.

Sections Four through Eight of this report include a case-by-case discussion of applicable emission control technologies and achievable emissions standards for diesel engines used in each class of off-highway equipment. Table E-3 summarizes the emissions standards estimated to be achievable by each class, as well as the percentage reduction from present levels represented by these standards. In the intermediate term, engines in all classes except farm equipment and construction equipment were estimated to be capable of meeting emissions standards comparable to the California 1988 NO_x and PM standards for on-highway vehicles, using essentially existing technology. Construction and farm equipment were estimated to require a higher NO_x limit, due to the limited potential for turbocharging and aftercooling.

Given time to develop advanced emission control technology, it was estimated that engines in railway locomotives and marine vessels would be able to comply with emissions standards comparable to the Federal 1991 standards for on-highway vehicles, while those in mobile refrigeration units should be able to comply with standards comparable to the 1994 on-highway limits. Construction and farm equipment could meet PM standards similar to the 1994 levels, but--due to their higher load factors--might not be able to achieve the level of 0.10 g/BHP-hr mandated for on-highway engines. As is also true of on-highway engines, a reduction in diesel fuel sulfur content might be required to achieve these low particulate levels. In addition, construction

TABLE E-3. EMISSIONS STANDARDS ESTIMATED TO BE ACHIEVABLE BY EACH CLASS OF OFF-HIGHWAY DIESELS

	Intermediate		Advanced Technology	
	Standard (g/BHP-hr)	Percent Reduction	Standard (g/BHP-hr)	Percent Reduction
Locomotives				
NO_x	6.0	55%	5.0	63%
HC	0.50	52%	0.30	71%
PM	0.50	1%	0.20	60%
Marine Vessels				
Medium-Speed Engines				
NO_x	6.0	55%	5.0	63%
HC	0.50	52%	0.30	71%
PM	0.50	1%	0.20	60%
High-Speed Engines				
NO_x	6.0	45%	5.0	55%
HC	0.50	38%	0.50	38%
PM	0.50	17%	0.25	59%
Farm Equipment				
NO_x	8.0	30%	6.0	48%
HC	0.50	72%	0.20	89%
PM	0.50	60%	0.15	88%
Construction Equipment				
NO_x	8.0	12%	6.0	34%
HC	0.50	32%	0.20	73%
PM	0.50	36%	0.15	81%
Mobile Refrigeration				
NO_x	6.0	49%	5.0	58%
HC	1.0	10%	0.20	73%
PM	0.50	2%	0.10	80%

Source: Radian estimates.

and farm equipment would also require a slightly higher NO_x limit than that mandated for on-highway engines, due to the limited potential for low-temperature charge cooling.

The reader is warned that the emissions limits shown in Table E-3 are engineering estimates only, based on very limited data, and intended only to indicate the potential benefits of regulation in this area. As discussed below, additional research to confirm these estimates would be essential before these or any other emission standards were incorporated into law.

Figures E-1 through E-3 show the potential effects of introducing the emissions standards listed in Table E-3 on NO_x, HC, and PM emissions from each class of off-highway engines. The leftmost bar for each class represents the current situation, with no emissions control. The middle bar represents the emissions that would be experienced if all existing engines met the "intermediate" emissions standards, and the rightmost bar the emissions that would result if all existing engines met the "advanced technology" standards. The net reduction if every off-highway engine in use met the "advanced technology" standards would be about 1.4 million tons of NO_x, 162,000 tons of HC, and 146,000 tons of PM per year, or 52 percent, 70 percent, and 78 percent, respectively, of the current emissions of these pollutants from off-highway diesels. In reality, of course this would take a very long time to achieve, due to the need to turn over the existing engine population.

The cost-effectiveness of controlling off-highway diesel emissions to at least the intermediate-term standards shown is estimated to be very favorable compared to the costs of other available emission control measures of similar significance. Estimated cost-effectiveness values for a number of specific equipment types are shown in Table E-4. While based on crude preliminary cost estimates, these values are believed to somewhat conservative (in the sense of over-stating emissions control costs, and thus the costs per ton of pollutants eliminated). Despite this, the cost-effectiveness estimates for control of NO_x and HC range from a few hundred to about three thousand dollars per ton.

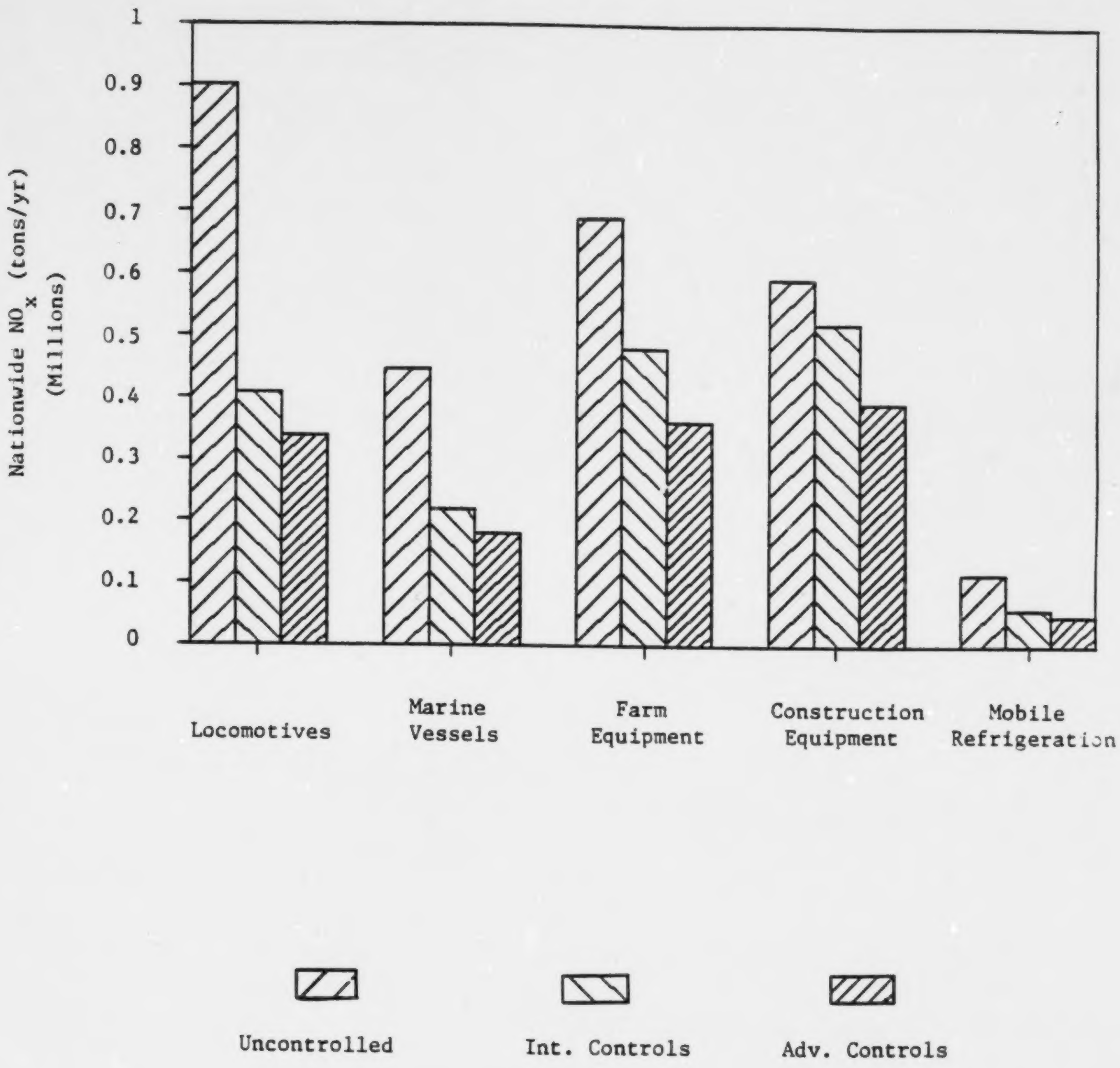

Figure E-1. Estimated Effect of Emissions Controls on Total Off-Highway NO_x Emissions

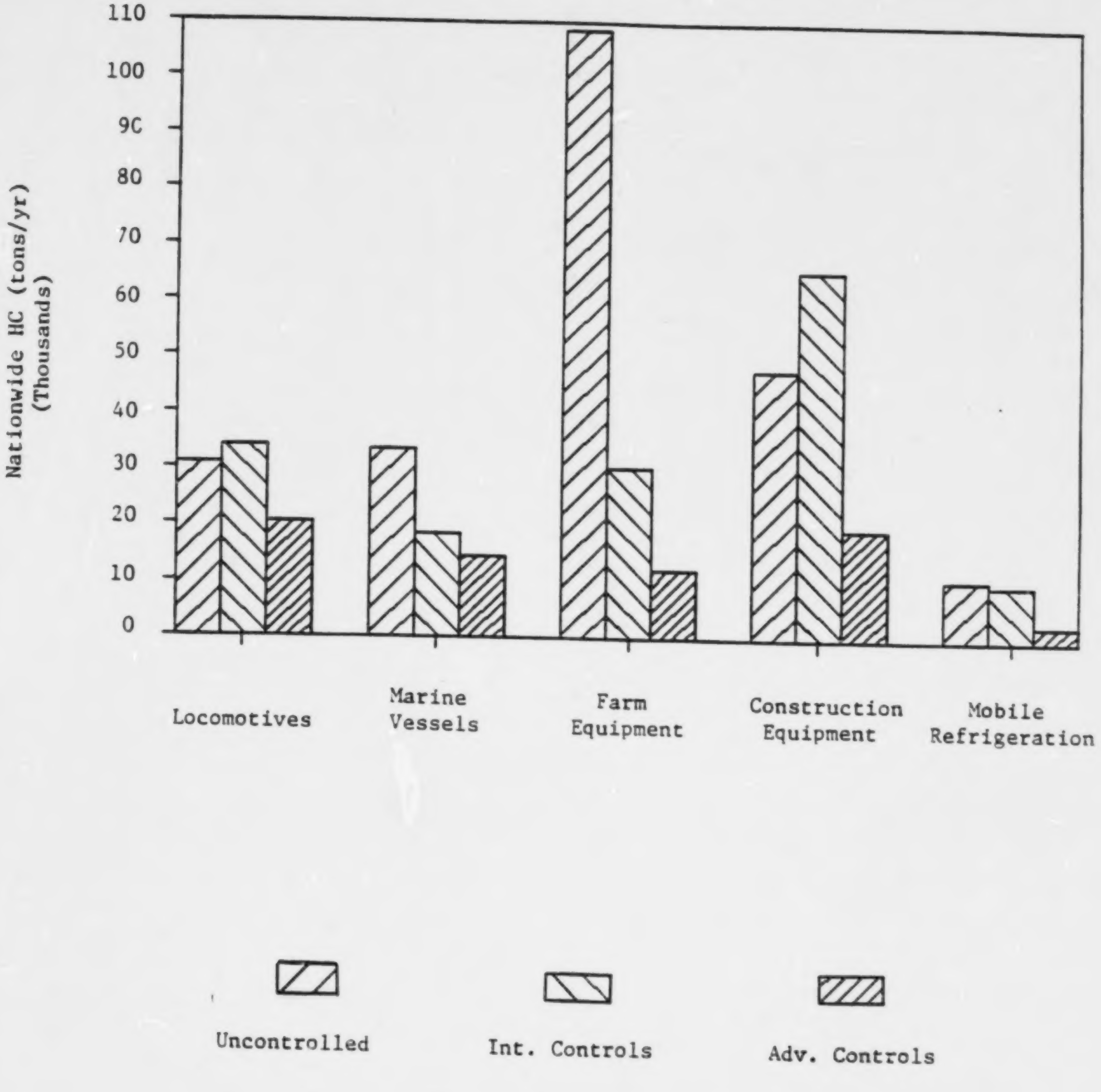

Figure E-2. Estimated Effect of Emissions Controls on Total Off-Highway HC Emissions

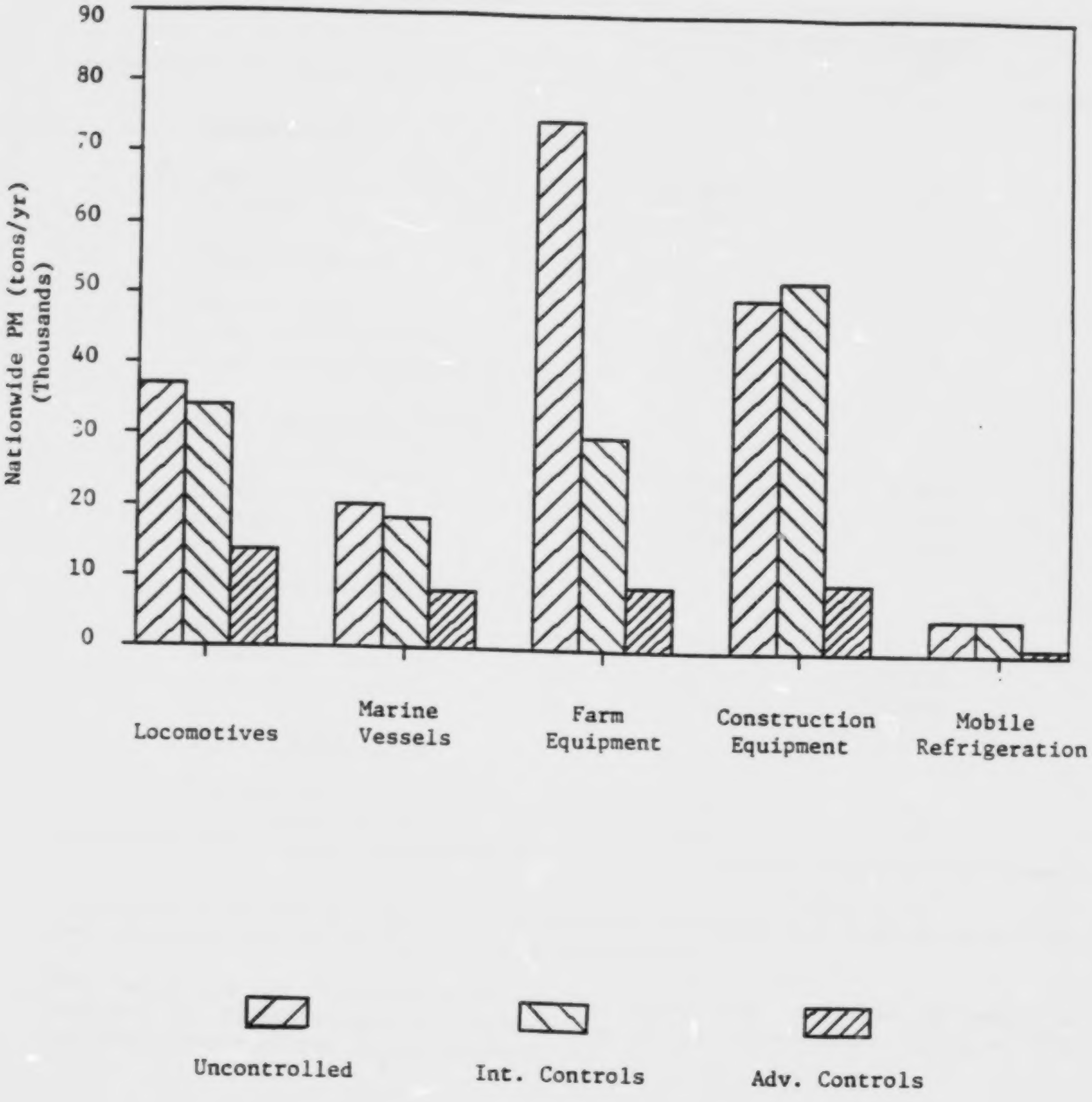

Figure E-3. Estimated Effect of Emissions Controls on Total Off-Highway PM Emissions

TABLE E-4. ESTIMATED COST-EFFECTIVENESS OF "INTERMEDIATE LEVEL" EMISSIONS CONTROLS FOR DIFFERENT CLASSES OF OFF-HIGHWAY VEHICLES

	Cost Effectiveness ($/ton)[1]	
	NO_x + HC	PM
Locomotives		
New	$1,073	--[2]
Retrofit	1,332	--[2]
Marine Vessels		
Medium Speed	672	--[2]
High-Speed Propulsion	888	--[2]
High-Speed Generator	616	--[2]
Farm Equipment		
Large 4WD Tractor	845	3,067
Small Tractor	2,960	7,607
Combine	848	1,900
Construction Equipment		
Hydraulic Excavator	748	8,969
Industrial Tractor	1,567	5,323
Concrete Paver	2,045	3,961
Mobile Refrigerator		
Railcar Unit	229	--[2]
Truck/Container Unit	1,909	--[2]

[1] Approximate estimates based on engineering judgement and limited data. See text Chapters 4-8 for assumptions and limitations.

[2] PM reductions at "intermediate" control level are estimated as small or negative for these categories. This is due to low PM emissions to begin with, and the effects of the NO_x/PM tradeoff.

For comparison, the fuel cost alone for reducing the 1991 NO_x standard for heavy-duty on-highway engines from 5.0 to 4.0 g/BHP-hr (a step which is often suggested) is estimated at about $2,000 per ton (assuming a 4 percent fuel economy penalty and fuel at $0.80 per gallon excluding taxes). The incremental cost-effectiveness of the 1994 PM standard of 0.1 g/BHP-hr for heavy-duty on-highway engines has been estimated at about seven to eleven thousand dollars per ton (Weaver and Klausmeier, 1987a).

Recommendations

1. The development of more accurate and representative duty cycles, emission factors, and emission inventories for off-highway diesel vehicles would be highly desirable, as would the development of suitably representative emissions test procedures. These data and procedures would be valuable in developing and evaluating any future regulations in this area. However, EPA funding of emissions control experimentation is not recommended beyond a very preliminary level. Experience has shown that this type of work is more appropriately left to the engine manufacturers.

2. Were emissions regulations to be established for farm and construction equipment engines, careful consideration should be given to phase-in mechanisms in order to avoid undue burden on the industry. An averaging, trading, and banking approach with "crawling" target levels, such as that discussed in Section 6.5, would be one fairly straightforward way to do this.

3. In the event that emissions regulations are established for new medium-speed marine and locomotive engines, consideration should also be given to establishing retrofit requirements for older engines in these categories. These requirements could most conveniently apply at the time of rebuild.

Limitations and Caveats

This report presents the results of a preliminary investigation of controlling emissions from off-highway diesel vehicles. The principal purpose of this investigation was to determine whether these vehicles offer sufficient potential for technically feasible and cost-effective emission reductions to justify further attention from EPA. The study results indicate that regulation of off-highway emissions could potentially result in large, cost-effective emission reductions. Thus, further investigation and possible regulatory action are indicated. However, this investigation does not conclusively demonstrate, and should not be interpreted as demonstrating that the levels of emissions control assumed here are technically feasible, or achievable within any particular time frame, or at any particular cost. Many issues remain to be resolved before any realistic emissions standards or compliance schedules could be established.

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1.0 INTRODUCTION

Diesel engines in off-highway vehicles and other off-highway mobile equipment, while less numerous than those in highway trucks and buses, are still significant contributors to NO_x and particulate inventories in many urban areas. These engines are presently exempt from any emissions control requirements. Consequently, they produce far more pollution (per unit of fuel input or work output) than the otherwise similar emission-controlled engines used in on-highway vehicles. The recent promulgation of stringent NO_x and particulate emissions standards for diesel engines in on-highway vehicles has drawn attention to diesel emissions in general, and has raised the question of whether similar emissions standards might not be appropriate for off-highway diesel engines.

1.1 Background

Emissions from diesel engines used in on-highway trucks and buses have been regulated with increasing stringency since 1972. New Federal regulations adopted in 1985 will limit particulate matter (PM) emissions from heavy-duty diesel engines to 0.6 grams per brake horsepower-hour (g/BHP-hr), beginning in the 1988 model year. The NO_x emissions limit, currently at 10.7 g/BHP-hr, will be reduced to 6.0 g/BHP-hr in 1990, and to 5.0 g/BHP-hr in 1991. A new PM limit of 0.25 g/BHP-hr (0.1 g/BHP-hr for buses) is also scheduled for 1991, and a PM limit of 0.1 g/BHP-hr for all vehicles is scheduled for 1994.

Although they are technically very similar to on-highway diesel engines, engines used in off-highway mobile equipment such as locomotives, farm and construction equipment, boats, and similar applications are presently exempt from any emissions standards. The Clean Air Act gives EPA authority to regulate "stationary sources" of emissions, and "motor vehicles", but EPA interprets the term "motor vehicle" to include on-highway vehicles only. Since off-highway mobile sources are neither "stationary" nor "motor vehicles", EPA considers that it has no authority to regulate them. EPA does have authority to regulate emissions from stationary internal-combustion engines used for cogeneration, emergency generators, irrigation pumping, and so forth, but New Source Performance Standards (NSPS) for these engines have not been promulgated.

1.2 Nature and Scope of This Report

Radian Corporation was commissioned by the U.S. EPA, Office of Policy Analysis to study the feasibility and cost-effectiveness of emissions controls in off-highway diesel vehicles. This document is the final report of that study. This report addresses the following major categories of diesel-engined off-highway equipment:

- Railroad locomotives;
- Marine vessels (except large oceangoing ships);
- Farm equipment;
- Construction and industrial equipment (including mining and forestry equipment); and
- Mobile refrigeration units.

These categories include all large groups of mobile diesel engines except for on-highway vehicles (which are already regulated) and oceangoing motorships. Engines used for generators, pumps, and compressors and diesel lawn and garden equipment were also included in the original scope of the study, and these (along with all the categories listed above) were examined in a preliminary report (Weaver and Pugh, 1986). They were subsequently dropped, due to their insignificant contribution to total emissions.

Table 1-1 gives an idea of the relative importance of on-highway and off-highway diesel engines. This table lists U.S. Department of Energy estimates of the amount of distillate diesel fuel consumed by each equipment

TABLE 1-1. DELIVERIES OF DIESEL FUEL FOR ON- AND OFF-HIGHWAY VEHICLES AND EQUIPMENT

Class	Annual Deliveries 1000s of Gallons
Farm	3,161,338
Locomotive	3,209,729
Marine Vessels	1,894.265
Construction and Other Off-Highway	1,616,685
Off-Highway Total	9,882,017
On-Highway Total	17,279,650
Total Mobile Diesel Engines	27,161,667
Off-Highway as Percent of Total	36.4%

Source: EIA, 1985.

category in 1985. As this table indicates, each of the individual categories of off-highway mobile sources considered in this report is small compared to on-highway vehicles (trucks, buses, and diesel passenger cars). Collectively, however, these sources are quite significant. As can be seen, total off-highway diesel fuel consumption is equal to 57 percent of the on-highway total. Furthermore, some of the fuel used in the on-highway category is used for powering mobile refrigeration units. Emissions from these units are unregulated, and they are covered in this report. It is apparent that off-highway and other unregulated diesel emissions sources must account for a very significant fraction of total diesel engine emissions in the United States.

1.3 Guide to the Remainder of the Report

This report is divided into nine sections, of which this Introduction is the first. Section Two, following, provides the technical background for the succeeding sections. It discusses the classification and general characteristics of off-highway diesel engines, and the fundamentals of diesel emissions. Section Three discusses the current state of the art in diesel emissions control, based largely on on-highway engine results. Sections Four through Eight each deal with one of the equipment categories listed in Section 1.2 above. Engine characteristics and operating conditions, estimates of current emission factors, and a discussion of applicable emission control technology are given for each category. Estimates of the total engine population, fuel use, and nationwide pollutant emissions for each category are also presented in each section.

Following the five sections dealing with individual engine categories, Section Nine summarizes the results of the study and our conclusions. This section also contains our recommendations for further research, and for policy action.

1.4 Limitations and Caveats

This report presents the results of a preliminary investigation of controlling emissions from off-highway diesel vehicles. The principal purpose of this investigation was to determine whether these vehicles offer sufficient potential for technically feasible and cost-effective emission reductions to justify further attention from EPA. The study results indicate that regulation of off-highway emissions could potentially result in large, cost-effective emission reductions. However, this investigation does not demonstrate, and should not be interpreted as demonstrating that any particular level of emissions control is technically feasible, or achievable within any particular time frame, or at any particular cost.

While this report presents some approximate estimates of the emission levels achievable, and the costs of achieving them, the reader is cautioned not to misinterpret these. These are preliminary estimates only, made for the purpose of assessing what might be achieved through regulations--they are not definitive. Many issues remain to be resolved before any realistic emissions standards could be specified. These issues include: representative test cycles for the different off-highway applications; emissions levels from existing engines using these representative test cycles; effects of available emission control techniques on emissions measured over these test cycles; actual costs of vehicle redesign to accommodate emission controls; feasibility of some emission control techniques in some applications; and the potential for emissions compliance through use of alternative fuels such as methanol and compressed natural gas. Further research and much more detailed evaluation of each of these issues would be required before any regulations could be adopted.

2.0 DIESEL ENGINE CHARACTERISTICS AND CLASSIFICATION

This section provides an overview of diesel engine characteristics and technology, diesel pollutant emissions, and emission regulations. It is intended to supply background information for those previously unfamiliar with diesel engines and emissions control, and to establish definitions for the more technical chapters which follow.

2.1 Engine Classification

Diesel engines are conventionally divided into three major classes on the basis of size and rotational speed (Lilly, 1984). These classes are:

1. Slow-speed engines (0-600 RPM)
2. Medium-speed engines (600-1300 RPM)
3. High-speed engines (1300 RPM up)

Slow-speed engines are used only in large ships (where they are typically direct-coupled to the propeller driveshaft), and in a very few stationary applications. They will not be considered further in this report. Medium-speed engines are used in railway locomotives, ships and large boats, as well as stationary generating and pumping applications. High-speed engines are by far the most numerous class, being used in highway trucks and buses, construction machinery, boats, farm equipment, and numerous other applications.

Due to the economics of mass production, diesel engines used in mobile off-highway applications are typically members of a family or series of engines sharing the same basic cylinder dimensions, but with varying types of aspiration (naturally aspirated, turbocharged, or turbocharged/aftercooled) and numbers of cylinders. Thus, a wide range of power requirements can be satisfied using the same basic combustion system. As an extreme example, the venerable Detroit Diesel-Allison 71 series engines are available in roots blown and turbocharged versions, with air-air or air-water aftercooling, and with 2, 3, 4, 6, 8, 12, or 16 cylinders.

Table 2-1 lists a number of the more popular engine series, along with some of their key technical characteristics. These characteristics are discussed in Section 2.2.

As Table 2-1 indicates, off-highway diesel engines can be grouped into several general groups.

1. Medium-speed engines used in railway locomotives and marine vessels.

2. Medium-sized, high-speed engines similar to those used in heavy-duty trucks. This is the largest group of off-highway diesel engines. Four, six, and eight-cylinder engines in this class are commonly used in agricultural and construction machinery and (in emission-controlled versions) for highway trucks. Larger 12 and 16-cylinder engines in the same series are used in marine and heavy construction applications.

3. Large high-speed engines, having sizes and power levels greater than those used in on-highway truck applications. Turbocharged and often intercooled, these engines are used mostly in marine and heavy earthmoving applications.

4. Small high-speed engines (often derived from light-duty automotive technology), and typically ranging from 10 to about 80 horsepower. These engines are mostly naturally-aspirated, and may use either direct or indirect injection.

TABLE 2-1. CHARACTERISTICS OF SOME COMMON OFF-HIGHWAY ENGINE SERIES

Engine Series	Disp. (1/cyl)	Bore (in.)	Asp. Types	Inj. System	Config. Offered	Horsepower Range	Application
Class 1: Medium-Speed							
GM Electromotive Division							
567	9.3	8.5	B,TA	UI	V8,V12,V16	600-2750	R,B,G
645	10.6	9.1	B,TA	UI	V8,V12,V16,V20	800-3900	R,B,G,C
710	11.7	9.1	TA	UI	V8,V12,V16,V20	1800-4800	R,B,G
General Electric							
FDL			N,TA	UI	V8,V12,V16	1800-3600	R
Caterpillar							
3600	18.5	11.0	TA	UI	6L,8L,V12,V16	1300-4500	R,B,G
Class 2: High-Speed, Truck Type							
Caterpillar							
3200	1.31	4.5	N,T,TA	IL	4L,V8	71-355	T,C,A
3300	1.75	4.8	N,T,TA	IL	4L,6L	85-335	T,C,A,G
3400	2.44	5.4	T,TA	IL	6L,V8,V12	215-838	T,C,A,G,B
Cummins							
NH	2.33	5.5	T,TA	UI	6L,V12	250-900	T,A,C,B,G
L10	1.67	4.9	T,TA	UI	6L	250-290	T,A,C,G
B	0.98	4.0	N,T,TA	IL	3L,4L,6L	66-177	T,A,C
C	1.38	4.5	N,T,TA	IL	6L	150-234	T,A,C
GM Detroit Diesel-Allision Division							
92	1.51		B,T,TA	UI	V6,V8,V12,V16	270-960	T,A,C,B,G
71	1.17	4.25	B,T,TA	UI	2L,3L,4L,6L, V6,V8,V12,V16	64-760	T,A,C,B,G
John Deere							
300	0.98	4.19	N,T	DP	3L,4L,6L	56-142	C,A,(T)[1]
400	1.27	4.56	N,T,TA	DP	6L	134-226	C,A,(T)[1]
Class Three: Large High-Speed Engines							
Caterpillar							
3500	4.31	6.7	TA	UI	V8,V12,V16	600-2000	C,B,G
300	4.03	6.3	TA	IDI	V8,V12,V16	500-1000	C,B,G

(Continued)

This grouping has important implications for emissions control. Engine series in Group 2, for instance, typically have at least one member used in on-highway trucks. As will be discussed in Section 3.1, emission control development for on-highway engines is already highly advanced. Transferring this technology to the off-highway engines in the same series would, in most cases, be straightforward. Similarly, engine technology in Group 3 resembles (except for the larger number of cylinders) that used in the heaviest on-highway trucks. The small high-speed engines in Group 4 resemble, in many cases, those used or being developed for light-duty automobiles, and could presumably utilize similar emission controls. Group 1 engines, on the other hand, have never been subject to stringent emission control requirements, and have no close analogs which have been. Development of emission controls for this group is likely to be more time-consuming and expensive than for the other groups.

2.2 Engine Technology

From an emissions control standpoint, the key technical features of a diesel engine are the following:

- combustion system;
- fuel injection system; and
- aspiration (air supply) system.

This section discusses the different types of systems in use.

Combustion Systems--Diesel engines in off-highway applicat[illegible] use several different types of combustion systems. The most fundamental difference is between direct injection (DI) engines and indirect injection (IDI) engines. Figure 2-1 shows a typical combustion chamber of each type. DI engines can also be divided into high-swirl and low-swirl (quiescent chamber) designs.

In an indirect-injection engine, fuel is injected into a separate "prechamber," where it mixes and partly burns before jetting into the main

TABLE 2-1. (Continued)

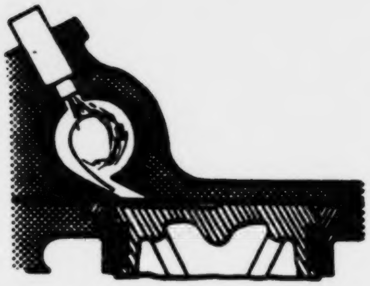
Engine Series	Disp. (l/cyl)	Bore (in.)	Asp. Types	Inj. System	Config. Offered	Horsepower Range	Application
Cummins							
K	3.14	6.25	T,TA	UI	6L,12V,16V	450-2000	C,B,G
GM Detroit Diesel-Allison Division							
149	2.45	5.75	B,T,TA	UI	8V,12V,16V	530-1800	
Class Four: Small High-Speed Engines							
Kubota							
3.23" St.	.37-.46	various	N,T	DP	3L,4L,6L	19-46	A,C,L
Yanmar							
TN82	0.46	3.23	N,T	DP	3L,4L	30-47	A,C,L
T95	0.78	3.74	N,T	DP	3L,4L	44-77	A,C,L

Aspiration
N - naturally aspirated
B - Roots-blown
T - turbocharged
TA - turbocharged/aftercooled

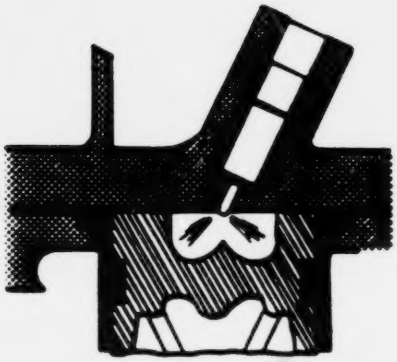
Combustion System
UI -- DI w unit injectors
IL -- DI w in-line pump
DP -- DI w distributor pump
IDI - indirect injection

Applications
T - On-highway trucks
A - Agricultural Equipment
C - Construction/Mining/Industrial equipment
B - Boats
L - Locomotive
G - Generators/stationary power
Rf - Mobile refrigeration

[1] Truck versions of these engines are under development.



(a) Indirect injection



(b) Direct injection

Figure 2-1. Diesel Engine Combustion Systems.

combustion chamber above the piston. In the more common direct-injection engine, fuel is injected directly into a combustion chamber hollowed out of the top of the piston. Fuel-air mixing in the direct-injection engine is limited by the fuel injection pressure and any motion imparted to the air in the chamber as it entered.

In high-swirl DI engines, a strong swirling motion is imparted to the air entering the combustion chamber by the design of the intake port. These engines typically use moderate-to-high injection pressures, and three to five spray holes per nozzle. Low swirl engines rely primarily on the fuel injection process to supply the mixing. They typically have very high fuel injection pressures and six to nine spray holes per nozzle.

In the indirect-injection engine, much of the fuel-air mixing is due to the air swirl induced in the prechamber as air is forced into it during compression, and to the turbulence induced by the expansion out of the prechamber during combustion. These engines typically have better high-speed performance than direct-injected engines, and can use cheaper fuel-injection systems. Historically, IDI diesel engines have also exhibited lower emission levels than DI engines. With recent developments in DI engine emission controls, however, this is no longer necessarily the case.

Disadvantages of the IDI engine are the extra heat and frictional losses due to the prechamber. These result in a 5-10 percent reduction in fuel efficiency compared to a DI engine, and a correspondingly greater load on the cooling system. Because of these disadvantages, nearly all engines in Groups 1,2, and 3, now use direct injection, as do an increasing number of those in Group 4.

Fuel Injection Systems--The fuel injection system in a diesel engine includes the machinery by which the fuel is transferred from the fuel tank to the engine, then injected into the cylinders at the right time for optimal combustion, and in the correct amount to provide the desired power output. The quality and timing of fuel injection dramatically affect the engine's power, fuel economy, and emissions characteristics, so that the fuel injection system is one of the most important components of the engine.

The fuel injection system normally consists of a low pressure pump to transfer fuel from the tank to the system, one or more high-pressure fuel pumps to create the pressure pulses that actually send the fuel into the cylinder, the injection nozzles through which fuel is injected into the cylinder, and a governor and fuel metering system. These determine how much fuel is to be injected on each stroke, and thus the power output of the engine.

Three generic types of fuel injection systems are in common use. These are:

1. Systems with distributor-type fuel pumps, in which a single pumping element is mechanically switched to connect to high-pressure fuel lines leading to each cylinder in turn;

2. Systems with unitary fuel pumps having one pumping element per cylinder, connected to the injection nozzle by high-pressure fuel lines (often called "in-line pumps"); and

3. Systems using unit injectors, in which the individual pumping element for each cylinder is combined in the same unit with the injection nozzle, eliminating the high-pressure lines.

Distributor pumps are relatively inexpensive, but they are limited in the injection pressures they can achieve. For this reason, they are used mostly in indirect-injection engines. In-line pumps are capable of much higher injection pressures, and are used in many Group 2 engines, especially those produced by European and Japanese manufacturers. Unit injector systems are capable of the highest injection pressures (exceeding 25,000 PSI). These are used in all Group 1 and Group 3 engines, and in an increasing proportion of

Group 2 engines as well. The larger Cummins engines, most Detroit Diesel-Allison (DDA) engines, and several recently-introduced Caterpillar engines use unit injectors.

Distributor and in-line injection pumps are typically driven by a special driveshaft from the engine timing gears. This allows the injection timing to be varied by rotating the pump with respect to its driveshaft, using a sliding helical spline. The pumping elements in unit injector systems are driven by the engine camshaft, in the same way as the intake and exhaust valves. Until recently, injection timing in unit injector systems was fixed by the system geometry (except for the effects of wear). With the addition of electronic controls, however, these systems can provide very flexible control of injection timing, as discussed in Section 3.1.

Aspiration Systems--The aspiration system is the system by which combustion air is provided to the engine. The first four-stroke diesel engines relied on the suction created by the intake stroke to draw air into the cylinder. This approach is known as natural aspiration, and it is still used on many smaller and lower-powered engines today. Since the pressure forcing the air into the cylinder is limited to that of the atmosphere, the air available for combustion (and thus the maximum power output) from these engines is limited.

In the early two-stroke engines, a separate Roots-type blower, driven from the crankshaft, provided combustion air at pressures slightly over atmospheric. This technique, again, is still used in many smaller and lower-powered two-stroke engines today. Roots-blown two-stroke engines, like four-cycle naturally-aspirated engines, are limited in their power output by the atmospheric pressure. Although not strictly accurate, it is common to lump these engines together with four-stroke engines as "naturally aspirated", a practice which will be followed here.

To obtain higher power output from a given engine size and displacement, manufacturers have adopted turbochargers. A turbocharger consists of a high-speed centrifugal compressor for the intake air, on the same shaft as and driven by a high-speed turbine in the exhaust. By compressing the intake air, the turbocharger increases the amount available in the cylinder, and thus the maximum power output.

Compressing the intake air increases its temperature, increasing the thermal loading on pistons and other components. Cooling the compressed air in a heat exchanger or aftercooler reduces the thermal load, and decreases the air volume, further increasing the air mass available in the cylinder and thus the maximum power output. Most high-powered diesel engines now incorporate turbocharging and aftercooling. For most such engines, the heat sink for the aftercooler is the engine cooling water, at a temperature of 80-95 C. The need for lower intake air temperatures in emission-controlled and high-output engines has resulted in increasing use of low-temperature aftercooling, using either air-to-air or air-to-low-temperature-liquid heat exchangers. These developments are discussed further in Section 3.1.

2.3 Diesel Emission Fundamentals

Diesel engines emit significant quantities of oxides of nitrogen (NO_x), sulfur oxides (SO_x), particulate matter (PM), and unburned hydrocarbons (HC). The NO_x, HC, and most of the PM emissions from diesels are formed during the combustion process, and can be controlled by appropriate modifications to that process. The sulfur oxides, in contrast, are derived directly from sulfur in the fuel, and the only feasible control technology is to reduce fuel sulfur content. Most SO_x is emitted as gaseous SO_2, but a small fraction (typically 2-3 percent) occurs as particulate sulfates.

Diesel particulate matter consists mostly of three components: soot formed during combustion, heavy hydrocarbons condensed or adsorbed on the soot, and particulate sulfates. In older-technology diesels, soot is typically 40 to 80 percent of the total particulate mass. Developments in in-cylinder emissions control for on-highway engines have reduced the soot contribution to particulate emissions considerably, however. Most of the remaining particulate mass consists of heavy hydrocarbons adsorbed or condensed on the soot. This is referred to as the soluble organic fraction of the particulate matter, or SOF. The SOF is derived partly from the lubricating oil, partly from unburned fuel, and partly from compounds formed during combustion.

The particulate SOF and gaseous hydrocarbons from diesel engines include many known or suspected carcinogens and other toxic air contaminants. These include polynuclear aromatic compounds (PNA) and nitroaromatics, formaldehyde and other oxygenated hydrocarbons. These last are also responsible for much of the characteristic diesel odor.

NO_x/Particulate Tradeoff--Diesel particulate and NO_x emissions result from the fundamental nature of the combustion process, making them especially difficult to control. As opposed to spark-ignition engines (which use a more-or-less homogeneous charge) all diesel engines rely on heterogeneous combustion. During the compression stroke, a diesel engine compresses only air. Fuel is injected into the combustion chamber in liquid form near the top of the compression stroke. The quantity of fuel injected with each stroke is determined by the engine power output required. After a brief period known as the ignition delay, the fuel is ignited by the hot air and burns. In the premixed burning phase, the fuel/air mixture formed during the ignition delay period burns rapidly. The subsequent rate of burning is controlled by the rate of mixing between the remaining fuel and air, with combustion always occurring at the interface between the two. Most of the fuel burned is burned in this diffusion burning stage, except under very light loads.

The fact that fuel and air must mix before burning means that a substantial amount of excess air is needed to ensure complete combustion of the fuel within the limited time allowed by the power stroke. Diesel engines, therefore, operate at overall air-fuel ratios which are considerably lean of stoichiometric. The air-fuel ratio during a given stroke is determined by the engine power requirements, which govern the amount of fuel injected.

The minimum air-fuel ratio for complete combustion in a diesel is about 21, corresponding to about 50 percent excess air. This ratio is known as the smoke limit, since smoke increases dramatically at ratios lower than this. The smoke limit establishes the maximum amount of fuel that can be burned per stroke, and thus the maximum power output of the engine.

NO_x in the diesel engine is primarily NO, which is formed at high temperatures close to the flame front in the presence of excess oxygen. The rate of NO formation in diesels is a function of oxygen availability, and is exponentially dependent on the flame temperature. In the diesel engine, most of the NO_x emitted is formed early in the combustion process, when the piston is still near top-dead-center (TDC). This this is when the temperature and pressure of the charge are greatest. Recent work by several manufacturers and consultants (Wade et al., 1987; Cartellieri and Wachter, 1987; mfrs. confidential data) indicates that most of this NO_x is actually formed during the premixed burning phase, and that reducing the amount of fuel burned in this phase can significantly reduce NO_x emissions. NO_x can also be reduced by actions which reduce the flame temperature during combustion. These actions include: delaying combustion past TDC, cooling the air charge going into the cylinder, reducing the air-fuel mixing rate near TDC, and exhaust gas recirculation (EGR). Since combustion always occurs under near-stoichiometric conditions, reducing the flame temperature by "lean-burn" techniques, as in spark-ignition engines, is impractical.

Diesel soot is formed only during the diffusion burning phase of combustion. Most of the soot formed is subsequently burned during the later portions of the expansion stroke. Soot oxidation is much slower than soot formation, however, and the amount of soot oxidized is heavily dependent on the availability of high temperatures and adequate oxygen during the later stages of combustion. Actions which decrease the amount of fuel burned in the diffusion burning stage tend to decrease soot emissions (at the cost of an increase in NO_x). Actions which reduce the availability of oxygen (such as EGR, or operation at low air-fuel ratios), or which reduce the time available for soot oxidation (such as retarding the combustion timing or reducing the air-fuel mixing rate) tend to increase soot emissions.

Diesel HC emissions (as well as the unburned-fuel portions of the particulate SOF) occur primarily at light loads, as a result of excessive fuel-air mixing, producing a mixture too lean to burn. Other HC sources include fuel deposited on the combustion chamber walls by the injection process, fuel retained in the orifices of the injector which vaporizes late in combustion, and partly reacted mixture which is subjected to bulk quenching by too-rapid mixing with air. Advanced injection timing (especially at light loads and high speeds), higher bulk gas temperatures, and lower injection pressures tend to reduce HC emissions; high air swirl rates and high injection pressures tend to increase them.

It is apparent from the foregoing discussion that there is an inherent conflict between some of the most powerful diesel NO_x control techniques and particulate emissions. This is the basis for the much-discussed "tradeoff" relationship between diesel NO_x and particulate emissions. This "tradeoff" is not absolute--various NO_x control techniques have varying effects on soot and HC emissions, and the importance of these effects varies as a function of engine speed and load. These tradeoffs do place limits on the extent to which any one of these pollutants can be reduced, however. To minimize emissions of all three pollutants simultaneously requires careful optimization of the fuel injection, fuel-air mixing, and combustion processes over the full range of engine operating conditions.

Visible Smoke--Visible smoke is due primarily to the soot component of diesel particulate matter. Under most operating conditions, the exhaust plume from a properly adjusted diesel engine is normally invisible, with a total opacity (absorbtance and reflectance) of two percent or less. Visible smoke emissions from heavy-duty diesels are typically due to operating at air-fuel ratios at or below the smoke limit, or to poor fuel-air mixing in the cylinder. Poor mixing may occur during "lug-down" (high-torque operation at low engine speeds) since turbocharger boost, air swirl level, and fuel injection pressure are typically poorer in these "off-design" conditions. Marginal air-fuel ratios also occur in full-power operation of naturally-aspirated engines, resulting in some visible smoke under these conditions.

In turbocharged engines, low air-fuel ratios can occur during transient accelerations, since the inertia of the turbocharger rotor means that the air supply during the first few seconds of a full-power acceleration is less than the air supply in steady-state operation. To overcome this problem, turbocharged engines in highway trucks incorporate an acceleration smoke limiter, which limits the fuel flow to the engine until the turbocharger has time to respond. This reduces the transient power and torque available from the engine, however. For this reason, smoke limiters are not commonly used in most off-highway applications.

2.4 Emission Regulations

Emissions from diesel engines used in on-highway trucks and buses have been regulated since 1972. Due to the variety of heavy-duty truck sizes, types, and applications, it has been considered impractical to specify heavy-duty emissions limits in terms of pollution per unit of distance travelled (e.g. grams per mile), as is done for light-duty vehicles. Instead, heavy-duty emissions regulations are written to apply to the engine, rather than the vehicle. The emissions limits are expressed in terms of grams of pollution per unit of work output from the engine, as measured over a specified test cycle on an engine dynamometer. The specific units of the U.S. regulations are grams of pollution per brake horsepower-hour (g/BHP-hr).

Federal and California emissions limits established for heavy-duty on-highway diesel engines are shown in Table 2-2. Regulated pollutants include

TABLE 2-2. FEDERAL AND CALIFORNIA EMISSIONS REGULATIONS FOR HEAVY-DUTY DIESEL ENGINES

	CO (g/BHP-hr)	HC (g/BHP-hr)		NO_x (g/BHP-hr)	PM (g/BHP-hr)	Test Procedure	Smoke Opacity (Acc/Lug/Peak, %)
Federal							
1974-1978	40		16[a]		NR	13-Mode	20/15/50
1979-1984	25	1.5	10[a]		NR	13-Mode	20/15/50
1985-1987	15.5	1.3		10.7	NR	Transient	20/15/50
1988-1989	15.5	1.3		10.7	0.6	Transient	20/15/50
1990	15.5	1.3		6.0	0.6	Transient	20/15/50
1991-1993	15.5	1.3		5.0	0.25	Transient	20/15/50
1994+	15.5	1.3		5.0	0.1	Transient	20/15/50
California							
1973-1974	40		16[a]		NR	13-Mode	b
1975-1976	30		10[a]		NR	13-Mode	b
1977-1979	25	1.0		7.5	NR	13-Mode	b
1980-1983	25	1.0	6.0[a]		NR	13-Mode	b
1984-1987	15.5	1.3		5.1	NR	Transient	b
1988-1990	15.5	1.3		6.0	0.6	Transient	b
1991-1993	15.5	1.3		5.0	0.25	Transient	b
1994+	15.5	1.3		5.0	0.1	Transient	b

NR: Not regulated

[a] Sum of NO_x plus HC emissions.

[b] Federal Smoke Standard applies.

carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx), and (beginning in model year 1988) particulate matter (PM). As a practical matter, however, only the NO_x and PM regulations are of much significance, since diesel HC and CO emissions are much lower than the standards (which were written for gasoline engines).

A separate regulation also limits the maximum smoke opacity for on-highway diesel engines. This had some effect in limiting particulate emissions prior to the establishment of the PM standard. However, compliance with future PM emissions limits will result in smoke opacity levels far below the regulated values, essentially rendering the opacity regulation irrelevant.

Test procedures--the test cycles and other procedures under which emissions are measured are as important as the numerical emissions limits. Until 1985, gaseous emissions were measured on the "13-mode" cycle. This cycle consisted of steady-state operation at ten different power and speed settings, with intervening periods of idle. Since diesel HC, CO, and PM emissions are heavily influenced by transient operation, the steady-state 13-mode procedure was considered a poor predictor of in-use emissions of these pollutants by highway vehicles. For this reason, it has been superseded by the current Federal Heavy-Duty Transient Test Procedure. In this procedure, engine speed and load are continuously varied according to a fixed schedule, which is intended to simulate typical urban driving.

Unlike highway trucks, most off-highway diesel applications include little transient operation (construction equipment is the major exception). Thus, the 13-mode cycle, with its steady-state operation, may produce more representative results than the transient procedure for these engines. This is fortunate, since virtually all of the available data on off-highway diesel emissions are based on the 13-mode or some other steady-state operating cycle. Appropriate test cycles for individual classes of equipment are discussed further in Sections Four through Eight.

3.0 TECHNOLOGY FOR EMISSIONS CONTROL

This section summarizes the current state of the art in diesel emissions control. Emissions control technology for high-speed, on-highway diesel engines has advanced rapidly over the last few years due to recent EPA and California ARB regulations imposing "technology forcing" emissions standards for the 1988, 1991, and 1994 model years. These developments are described at length in another Radian report (Weaver and Klausmeier, 1987), from which most of Section 3.1 has been adapted. Many of these developments are directly applicable to high-speed off-highway engines as well. Progress in controlling emissions from medium-speed engines has been much more limited. This is at least partly due to the lack of significant regulatory pressure on this engine class. Emission controls for these two engine classes are discussed separately below.

3.1 High-Speed Engines

Virtually all heavy-duty diesel engine manufacturers have mounted intensive research and development efforts in emissions control, in order to be able to comply with the 1988 and 1991 emissions standards. Compliance with the 1988 standards has been attained, and compliance with the far more stringent 1991 standards of 5.0 g/BHP-hr NO_x and 0.25 g/BHP-hr PM now appears within reach (Weaver and Klausmeier, 1987a). Since on-highway and off-highway engines are identical in their underlying technologies, all of the basic research performed in this effort should be applicable to off-highway engines as well. Much of the application and design work should also be directly applicable to off-highway engines in Group 2, and (to a lesser extent) Group 3. However, much detailed development and application engineering would still be needed to adapt these technologies to the different requirements and operating patterns of off-highway service.

Overview--Diesel engine emissions of NO_x, PM, and HC can be reduced by carefully tailoring the air induction, fuel injection, fuel-air mixing, and other elements of the combustion process. This in-cylinder emissions control is limited by the tradeoffs discussed in Section 2.3. Diesel emissions can also be reduced through aftertreatment--physical or chemical treatment of the exhaust gases after they leave the cylinder. Table 3-1 lists the significant emission control technologies in use or under development in each of these categories for on-highway engines.

The last few years have seen tremendous progress in the control of diesel engine emissions in the cylinder. As a result, it now appears likely that many on-highway engines--especially those used in the largest or "heavy-heavy" truck class--may be able to comply with the 1991 emissions standards by in-cylinder means alone. If certification testing were conducted with low-sulfur fuel, most new heavy-duty on-highway diesel engines would be able to meet the 1991 standards without the use of a trap, although some would require the use of a catalytic converter or other non-trap aftertreatment technique to reduce particulate emissions. These advances have also brought the 1994 particulate standards of 0.1 g/BHP-hr within the range of possibility, given an efficient trap and low-sulfur fuel (Weaver and Klausmeier, 1987a).

In-cylinder emissions control--Recent progress in in-cylinder emissions control has been made possible, in large part, by improved understanding of the diesel combustion process, and of the factors affecting pollutant formation and destruction. Pollutant formation and destruction in the cylinder are determined by the specific course of the diesel combustion process. Modifying this process to minimize pollution involves a complex multi-dimensional tradeoff between NO_x, HC, and PM emissions, fuel economy, power output, smoke, cold-start ability, cost, and many other considerations. These changes go to the heart of diesel engine design, and they have the potential either to dramatically enhance or dramatically degrade an engine's performance relative to its competitors. As a result, engine manufacturers have devoted the bulk of their research and development resources to this area.

Most engine manufacturers have followed a broadly similar approach to in-cylinder control, although the specific techniques used differ considerably

TABLE 3-1. TECHNIQUES FOR DIESEL ENGINE EMISSIONS CONTROL

IN-CYLINDER CONTROLS

- Fuel Injection System
  - Low sac/zero sac nozzles
  - Retarded (fixed) injection timing
  - Variable injection timing
  - High injection pressure
  - Transient smoke limiter
  - Governor curve shaping
  - Electronic fuel rate control
  - Electronic injection timing control
  - Reduced initial rate of injection
  - Variable fuel injection rate
- Air charging system
  - Turbocharging
  - Intercooling
    - Jacket Water
    - Air-air
    - Low flow air-water
    - Separate circuit air-water
  - Low-inertia turbocharger
  - Variable geometry turbocharger
  - Externally-driven turbocharger
  - Turbocompound engine
  - Mechanical supercharger
  - Gas-dynamic supercharger
- Combustion Chamber
  - Reduced crevice volume
  - Optimized compression ratio
  - Optimized air swirl ratio
  - Variable air swirl ratio
  - Re-entrant bowl combustion chamber
  - Heat insulation
  - Indirect injection
  - Air cell
- Reduced Oil Consumption
- Exhaust Gas Recirculation

Continued

TABLE 3-1 (Continued)

AFTERTREATMENT CONTROLS

- Trap-oxidizer Systems
  - Traps
    - Cellular cordierite ceramic monolith
    - Cellular mullite fiber trap
    - Ceramic foam
    - Conductive SiC monolith
    - Woven silica-fiber "candle" trap
    - Precious metal catalyzed wire-mesh trap
  - Regeneration Techniques
    - Diesel fuel burner/bypass
    - Electric heater/bypass
    - Exhaust temperature increase
    - Catalyzed trap
    - Catalytic fuel additives
    - Catalyst injection in exhaust
    - Reverse flow/recycling
- Catalytic Converters
  - Cellular monolith
  - Pellet-type
- Electrostatic Precipitator/agglomerator
- Selective Catalytic Reduction
- RapReNox Process

from one manufacturer to the next. This typical approach to in-cylinder emissions control includes the following major elements.

- Minimize parasitic HC and PM emissions (those not directly related to the combustion process) by minimizing nozzle sac volume and reducing oil consumption to the extent possible

- Reduce PM emissions at constant NO_x by refining the turbocharger/engine match and improving engine "breathing" characteristics. Many manufacturers are also experimenting with variable-geometry turbochargers to improve the turbocharger match over a wider speed range.

- Reduce PM and NO_x (with some penalty in HC) by cooling the compressed charge air as much as possible, via air-air or low-temperature air-water aftercoolers.

- Further reduce NO_x to meet regulatory targets by severely retarding fuel injection timing over most of the speed/load range. Minimize the adverse effects of retarded timing on smoke, starting, and light-load HC emissions via a flexible timing system to advance the timing under these conditions.

- Recover the PM increase due to retarded timing by increasing the fuel injection pressure and injection rate.

- Improve air utilization (and reduce PM emissions) by minimizing parasitic volumes such as piston/cylinder head clearance and piston top land volume.

- Optimize in-cylinder air motion through changes in combustion chamber geometry and intake air swirl to provide adequate mixing at low speeds (to minimize smoke and PM) without over-rapid mixing at high speeds (which would increase HC and NO_x).

- Control smoke and particulate emissions in full-power operation and transient accelerations through improved governor curve shaping and transient smoke limiting (generally through electronic governor controls).

With a few notable exceptions (such as air-air aftercooling), these technologies should be applicable to the great majority of Group 2 and Group 3 off-highway engines as well. Many would also apply to Group 4 engines, although the costs of some technologies (such as turbocharging and aftercooling) might prove prohibitive.

In addition to these generally used approaches, a number of other promising in-cylinder control techniques are under development by various manufacturers. These include variable air swirl devices for improved control of in-cylinder air motion over a range of speeds; fuel injection pumps with electronic control of the fuel injection rate; proprietary technology to minimize the initial fuel injection rate, thus reducing premixed burning and NO_x emissions; and innovative supercharging technologies to minimize or eliminate turbocharger lag. Turbocompound engines, which are being developed primarily for fuel economy reasons, will also help reduce emissions somewhat through increased engine efficiency.

It is striking that most of the in-cylinder emission reductions attained to date in on-highway engines have come from painstaking optimization and incremental improvements to engine design, rather than from the application of major new technologies. Technologies such as electronic timing control and governing have played a fairly minor role in reducing emissions, although they have certainly helped to offset some of the deleterious effects of emissions control on engine performance. This suggests that--as an interim solution--fairly substantial improvements in off-highway engine emissions might be obtainable quickly and at moderate cost through relatively minor design and calibration changes. This could result in off-highway emissions levels comparable to those in truck engines meeting the 1988 standards. To attain emission levels comparable to those mandated for 1991 would require (in most cases) complete redesign and re-optimization of the engine--a very time-consuming and expensive process.

Several technologies are conspicuously absent from the list of those under development for on-highway engines, due to their adverse effects on fuel economy or durability. The most significant of these are exhaust gas recirculation (EGR) and indirect injection. Properly modulated, EGR can significantly reduce NO_x emissions with a minimal increase in PM. Oil contamination and engine wear rates are increased by EGR, however, and manufacturers have been strongly resistant to its use. While relatively low in emissions, IDI engines are 5-10 percent less fuel efficient than DI engines, and have lost market share as a result. The primary advantage of these two technologies is their low initial cost. This makes them well suited to the small high-speed diesel engines in Group 4, for which their disadvantages of increased wear and fuel consumption are least significant.

Aftertreatment control technologies--Potential exhaust aftertreatment technologies include trap-oxidizers and flow-through catalytic converters, both of which would affect primarily PM and HC emissions. Due to the oxidizing nature of diesel exhaust, aftertreatment techniques for NO_x require that a separate reducing agent be supplied. Despite considerable publicity given to one such system, this approach is considered infeasible for general application in vehicles.

Most of the research and development activity in diesel aftertreatment involves trap-oxidizers. A trap-oxidizer system consists of a durable particulate filter in the exhaust (the "trap"), along with some means of regenerating the filter by burning off ("oxidizing") the collected particulate matter. Development activity is concentrated on the "oxidizer" portion of the system, as suitable filter media have been available for some time.

Progress in trap-oxidizer development has been slow. This is at least partly due to the limited resources being devoted to trap-oxidizer R&D. Only a few manufacturers appear to have devoted major efforts to trap-oxidizer system development. Foremost among these is Daimler-Benz, which has placed 50 prototype traps on buses operating in West Germany (Hardenberg, 1987). One other U.S. engine manufacturer has also devoted considerable effort to trap-oxidizer development, and has successfully accumulated more than 123,000 miles on a prototype system. Trap-oxidizers have also been tested successfully in a number of underground mining applications (Brev et al., 1987).

The feasibility of trap-oxidizers in off-highway applications would depend on the specific application and operating conditions. The application of trap-oxidizers in trucks has been slowed by the need to ensure regeneration under all possible operating conditions (including prolonged low-power operation), without intervention from the driver. Engines in many off-highway applications are subject to much higher and more consistent load factors than those in highway trucks. In addition, off-highway equipment operators tend to be more involved in monitoring and maintaining their equipment. A simpler (and thus less expensive) regeneration system would be feasible under these circumstances--indeed, such systems have seen good acceptance in underground mining. On the other hand, safety concerns (e.g. in boats) or packaging problems could rule out trap-oxidizer use in some off-highway applications.

The success of in-cylinder particulate control efforts has led several manufacturers to investigate the feasibility of flow-through catalytic converters for reducing particulate emissions. Given the low engine-out particulate levels seen on current development engines, and the high organic content of the particulate matter, the use of a catalytic converter now appears as a possibly viable approach. By oxidizing much of the particulate SOF, a catalytic converter could reduce particulate emissions by 25 to 35 percent, which would be enough to meet the 1991 standard. A catalytic converter system would be much simpler and less expensive than a trap-oxidizer, since the flow-through design of the catalytic converter avoids the problem of regeneration. The major drawback to the catalytic converter approach in trucks is sulfate production--they would probably be feasible only with low-sulfur fuel. Catalytic converters in off-highway applications would be subject to the same safety and packaging concerns discussed above for trap-oxidizers.

3.2 Medium-Speed Engines

Due to the lack of regulatory pressure, the development of emission controls for the medium-speed diesel engines in Group 1 has lagged considerably behind that for high-speed, on-highway engines. Most emissions-related work on medium-duty engines has focussed on control of visible smoke, or on improving power output and fuel economy, with emission reductions only a side-effect. A limited amount of work on NO_x emissions control (primarily for locomotives) has also been performed, as will be discussed below. In addition, some studies have examined the effects of alternative fuels such as methanol and water/fuel emulsions on locomotive emissions and efficiency.

Smoke/particulate control--Visible smoke from locomotives is an annoyance, and has been subjected to regulatory limits in various jurisdictions around the U.S. Poor public relations and soiling of railroad properties and rolling stock have also led to pressure to reduce smoke emissions. At the same time, many technical changes adopted to reduce fuel consumption and/or increase power output have also helped to reduce smoke emissions. Some of the changes since the early '70s have included: use of low-sac injection nozzles, higher fuel injection pressure, increased use of turbocharging, higher boost pressures, increased turbocharger efficiency, more effective aftercoolers, reduced parasitic volume, and improvements in cylinder air flow (Kotlin and Williams, 1975; EMD, 1978). These have resulted in visible smoke levels (at sea level) in the 3-5 percent opacity range at full load.

Due to the exhaust volumes involved, only a few measurements of medium-speed engine PM emissions have been performed. However, two sets of measurements on modern turbocharged locomotive engines performed at Southwest Research have shown low to moderate PM levels. Measured emissions ranged from about 0.26 g/BHP-hr for an EMD engine to 0.48 g/BHP-hr for a GE engine in a line-haul operating cycle. For a switch-engine duty cycle, emissions for the GE engine increased to about 0.8 g/BHP-hr, but those for the EMD engine did not increase at all. These data are discussed at greater length in Section Four.

The PM emissions from older-technology engines are hard to estimate. Measurements by EMD on a 20-cylinder, turbocharged, 1973 model engine gave cycle-average PM emissions of 0.445 g/BHP-hr (EMD, 1978). These data may not be fully comparable to the SWRI data, however, due to differences in measurement technique. The only other PM emissions data extant for older-technology engines come from SWRI's Roots-blown 2-567 engine (Baker, 1980). On 39-cetane fuel, brake-specific PM emissions from this engine ranged from 1.25 g/BHP-hr at full load to 0.7 g/BHP-hr at intermediate loads, and climbed to about 1.0 g/BHP-hr at light load. If these laboratory data are representative of comparable engines in the field, those engines must be emitting substantially more than 1.0 g/BHP-hr averaged over their duty cycle.

NOx control--To date, work on NO_x controls for medium-speed engines has been limited to laboratory studies, or to modifications to specific small groups of engines. Actual in-use NO_x emissions from locomotive and other medium-speed engines are completely uncontrolled, and--as a result--very high. Typical NO_x emission factors for locomotives and medium-speed marine engines are in the range of 10 to 16 g/BHP-hr. This is true even for very highly rated turbocharged/aftercooled engines, which would be expected to have lower NO_x emissions.

General Motors' Electromotive Division (EMD) has experimented with the use of retarded injection timing and increased injection rates in its 645-series engines. Data from tests on three 16-cylinder EMD engines with these modifications are shown in Table 3-1. As the table indicates, NO_x emissions were reduced by 52-67 percent (to 6 g/BHP-hr), at a cost in fuel

TABLE 3-2. EFFECT OF ENGINE MODIFICATIONS ON GM ELECTRO-MOTIVE DIVISION (EMD) 16V-64E ENGINE PERFORMANCE AND EMISSIONS

Model	Application	Maximum Rated Output (Hp at RPM)	Changes	Gaseous Emissions (g/bhp-Hr)			Fuel Consumption (Lb/bhp-Hr)	Smoke Opacity (%)
				NO_x	CO	HC		
E2, E8	Power Drilling	2200 at 900	None	18.1	0.8	0.39	0.400	--
			6 degree retard	11.1	1.9	0.39	0.410	--
			6 degree retard, add turbo, change, piston, liner, and camshaft	6.0	0.5	0.30	0.427	--
E7	Marine Supply	2875 at 900	None	12.4	0.9	0.3	--	5.0
			Modify to E7C, retard timing	6.0	0.6	0.25	--	6.4
E9C	Oil Well Drilling	3400 at 900	None	15.1	0.38	0.32	0.350	4.0
			13 degree retard, change injectors, and camshaft	6.1	0.50	0.26	0.375	6.6

Source: Mr. Hugh Williams, EMD, cited in Santa Barbara APCD (1987).

economy of about 7 percent. Smoke opacity was also increased somewhat, but HC emissions were reduced. PM emissions were not measured, but they were probably affected fairly little. PM emissions consist of soot plus heavy HC; the increase in smoke and reduction in HC would tend to offset each other.

Another NO_x reduction study was conducted under the direction of the Santa Barbara Air Pollution Control District (1987). In this study, emissions from two EMD 12-645 engines on the supply boat Chesapeake Seahorse were reduced from an estimated 13.9 g/BHP hr in the uncontrolled condition to an average 8.3 g/BHP-hr at full load with moderately retarded injection timing. Use of room-temperature water (rather than engine cooling water) in the aftercooler of the starboard engine reduced the intake temperature by 9 C at full load, and gave a further NO_x reduction from 7.8 g/BHP-hr to 7.1. Under cruise conditions, the reduced coolant temperature gave a 12 C reduction in intake air temperature (to about 62 C), reducing NO_x emissions from 9.2 to 7.6 g/BHP-h. Air-air intercooling, or a more efficient air-water intercooler could have given 3-4 times this temperature reduction, and would likely have produced NO_x emissions in the 6 g/BHP-hr range.

EPA has also funded studies of NO_x reduction techniques for EMD engines at Southwest Research Institute (Storment et al., 1974). The SWRI data show that retarded timing and EGR are both effective NO_x reduction techniques. Retarded injection timing reduced NO_x emissions by 26 to 38 percent, while 30 percent EGR reduced them by more than 50 percent, at the cost of a moderate increase in smoke opacity at full load. These studies were conducted with a Roots-blown 2-cylinder EMD 567 engine, however, and may thus be unrepresentative of the turbocharged/aftercooled EMD 645-series engines which make up most of the current population.

Only very limited data are available on NO_x emission reductions in four-stroke engines. The most common four-strokes are the GE locomotive engines, which have NO_x emission factors in the 11 to 19 g/BHP-hr range (Ingalls, 1985). No emission control data for these engines are available.

Caterpillar was able to provide some limited data on the effects of retarded injection timing in its 3600-series engines, however. These data show a reduction of 7.2 percent in brake-specific NO_x emissions at full load (from a base of about 10 g/BHP-hr) for every degree of injection timing retardation. This is achieved at the cost of a 3.7 percent reduction in power, 0.9 percent increase in fuel consumption, and about .06 g/BHP-hr increase in dry particulate matter (i.e. soot) emissions. The dry particulate matter increase was calculated from smoke opacity measurements; actual total PM emissions were not measured.

Alternative Fuels--Many medium-speed stationary engines are operated either wholly on natural gas or with dual natural gas/diesel fueling. Experiments with natural-gas fueled locomotive engines have been undertaken (Wakenell, 1987), and at least one locomotive fueled with compressed natural gas (CNG) has been tested in service (Olson and Reed, 1987). At present, manufacturers of stationary natural-gas engines are routinely guaranteeing NO_x emissions levels of 2.0 g/BHP-hr or less, using lean-burn techniques. The same lean-burn technology could conceivably be applied to mobile medium-speed engines.

Some limited experimental work with methanol use in medium-speed engines has also been undertaken (Wood and Storment, 1980; Baker, 1981). Problems with damaging combustion knock at high methanol substitution levels have been found, and the emissions benefits have not been large.

Feasibility of further emission controls--Although larger and slower-running, medium-speed engines are fundamentally similar to heavy truck engines in their basic combustion systems. Thus, most of the in-cylinder emission control techniques developed for truck engines should be readily adaptable to medium-speed engines as well. Some key emission control techniques applicable to medium-heavy diesel engines include: retarded injection timing in conjunction with increased injection pressure, electronically-controlled unit injectors, low-temperature aftercooling, and optimization of air flow and fuel-air mixing in the combustion chamber.

Given equivalent levels of emissions control development and technology, medium-speed engines would be expected to produce lower emissions levels than high-speed engines. More time is available for combustion due to their lower rotational speed, so that the pre-mixed burning phase (which produces much of the NO_x) should account for a smaller fraction of the total. For the same reason, the time available for the burn-out of soot particles formed during combustion is much greater, so that a smaller amount of soot should be emitted.

In addition, lubricating oil from the cylinder walls presently accounts for a large fraction of PM emissions in high-speed engines. Due to their greater cylinder volumes (resulting in a higher power to wall area ratio), it should account for a smaller fraction of medium-speed PM emissions. Finally, medium-speed engines normally operate under steady or quasi-steady state conditions, as opposed to the highly transient operating conditions experienced by truck engines. Assuming that the test cycle adopted reflected these conditions, the brake-specific PM and HC emissions from medium-speed engines would be expected to be lower for that reason alone.

4.0 LOCOMOTIVES

Railroad locomotives are overwhelmingly diesel powered, and their large numbers and large power output per unit make them one of the most significant off-highway emission sources. Railroading has undergone major changes in the last decade, due to the impact of higher interest rates, high fuel prices, and deregulation. These have resulted in a smaller number of locomotives being used more intensively than in the past, and in considerable technical upgrading of existing locomotives. These trends have probably had the effect of lowering railroad emissions (as well as fuel consumption) significantly. However, sales of new locomotives have dropped dramatically since the late '70s, resulting in a slower turnover of the existing fleet.

4.1 Engine Characteristics and Operating Conditions

Modern railway locomotives are almost exclusively diesel-electric. In this arrangement, the diesel prime mover drives an electric generator; current from which drives the individual electric traction motors that drive the wheels. This has the effect of isolating the diesel engine from changes in locomotive speed and load. The locomotive control system provides for eight engine/generator power levels or "notches", plus idle and dynamic brake (in which the wheel motors are used as generators to slow the train). In any given notch, the diesel engine runs at constant speed and load. Engine RPM and power output change only as a result of changes in the notch setting. Thus, transient effects on locomotive emissions are probably minimal.

In 1982, the average horsepower for all locomotives was 2,341 (Statistical Abstract of the U.S., 1985). Individual locomotives range from under 1,000 hp to over 7,000 hp (McDonald, 1986). Units 1,500 hp and below are generally used exclusively for switching and transfer purposes (moving small groups of cars around a switchyard, or delivering them within an urban area). Switching locomotives make up approximately 19 percent of the U.S. locomotive population (Ingalls, 1985). Larger general-purpose locomotives (typically 2,000 to 4,000 hp) are designed primarily for line-haul (intercity) operation. However, many larger general-purpose locomotives (especially older ones) are also used in switching and transfer applications. Based on data in Ingalls (1985), Radian estimated that about 8,700 of the 22,900 locomotives used in 1986 by U.S. Class 1 railroads were assigned to line-haul service, with the rest being used in switching and transfer applications. Line-haul operation is estimated to account for about 72 percent of total railroad fuel use, however (calculated from Ingalls, 1985).

The vast majority of diesel-electric locomotives are powered by medium-speed, large-bore diesel engines of 1,000 to 4,000 hp. Ninety-five percent of all U.S. locomotives in use were manufactured by just two companies: General Electric (14 percent) and the Electromotive Division (EMD) of General Motors (81 percent) (Ingalls, 1985). Most of the remainder were produced by Bombardier, a Canadian company, using Alco engines. Some of the recently-introduced Caterpillar 3600-series engines have also been used in locomotive applications.

EMD locomotives are powered by EMD-produced, large-bore, medium-speed (900-1,000 RPM maximum) two-stroke diesel engines driving electric generators. Current EMD general-purpose units are powered by turbocharged 16-cylinder engines of 645 and 710 cubic inch displacement per cylinder, and have a horsepower range from 2,200 hp to 3,950 hp. EMD offers switching locomotives powered by eight and twelve-cylinder versions of the 645 engine. These engines are typically Roots-blown and generate 1,100 hp to 1,650 hp.

The EMD 645 and 710-series engine families are direct descendents of the EMD 567-series Roots-blown locomotive engines originally introduced in 1938. This engine family has been continuously improved and uprated over the years with the addition of turbocharging, intercooling, increased displacement per cylinder (to 645 cubic inches in 1966, 710 in 1985), improved component designs, and higher power ratings. As a result of EMD's design philosophy, most of the improved components developed over the years can be retrofit to existing engines when they are rebuilt (Kotlin and Williams, 1975). As a result, many different versions of the EMD engines are now in service, incorporating varying levels of technology and having varying emissions levels.

General Electric line-haul and general purpose locomotives are also powered by large-bore, medium-speed diesel engines driving electric generators. GE general purpose units are typically powered by GE FDL-12 cylinder, 3,000 hp turbocharged engines and have a maximum speed of 70 mph. GE (and also ALCO) engines differ from EMD engines in using a four-stroke rather than a two-stroke cycle. The GE FDL series runs from an 8 cylinder, 1,800 hp unit to a pair of 16 cylinder, 3,600 hp units (Ingalls, 1985). Most current GE switching units are powered by high-speed (1800 RPM) diesel engines purchased from an outside supplier--typically twin Cummins 6 or 8 cylinder, 300 to 550 hp, 4 stroke, turbocharged engines.

4.2 Current Emission Factors

Gaseous emission factors (HC, CO, NO_x) and operating cycles for locomotives were addressed in a recent report by Southwest Research (Ingalls, 1985). Ingalls compiled and compared gaseous emission factors from a number of published reports and manufacturer's data. Emission factors for a number of specific engine technologies are shown in Table 4-1. Ingalls then combined the emission and fuel consumption factors shown in the table, using data on locomotive populations, to arrive at the composite emission factors shown in Table 4-2. However, Ingalls failed to account for the fact that older locomotives are likely to have been rebuilt using newer injector and combustion-system technology, and that the older and less-efficient locomotives probably see less intensive use. As a result, the composite factors shown in Table 4-2 probably overestimate HC and CO emissions somewhat, and may underestimate NO_x. Possible malfunctions and in-use deterioration would tend to increase HC and CO, possibly offsetting this effect.

TABLE 4-1. MEASURED LOCOMOTIVE EMISSIONS FROM PUBLISHED STUDIES EXPRESSED IN GRAMS PER HORSEPOWER HOUR ON LINE HAUL CYCLES

Engine Description	Number Tested	Avg. Emissions, g/bhp-hr, (range)		
		HC	CO	NO_x
		General Electric Engines		
FDL, old speed schedule (1957 to approx. 1974)	4	2.2 (1.7 to 2.5)	4.2 (3.6 to 4.5)	14.0 (10.9 to 18.9)
FDL, new speed schedule (approx. 1973 to present)	5	2.3 (2.0 to 2.6)	2.5 (2.0 to 3.0)	14.2 (10.4 to 19.7)
FDL, new speed sch. low sac injectors	1	0.6	1.8	10.7
		Electromotive Division		
EMD 567 spherical injectors pre 1959	1	2.7	6.4	12.1
EMD 567 needle injectors 1959 to 1966	1	1.2	10.7	9.8
EMD 567 low sac injectors (retrofit after 1972)	1	0.7	7.4	13.0
EMD 645E blown, needle injector (1966 to 1972)	unknown	1.1	10.8	12.5
EMD 645E turbo, needle injectors (1966 to 1972)		0.8 (0.7 to 0.9)	3.2 (2.5 to 4.0)	11.6 (8.7 to 11.6)
EMD 645F3B turbo, low sac injectors	unknown	0.4(a)	0.6(a)	14.1(a)

(a) on UIC/ORE cycle

Source: Ingalls (1985)

TABLE 4-2. EMISSION FACTORS FOR RAILWAY LOCOMOTIVES

Source	HC	CO	NO_x	PM
Ingalls (1985) Composite				
Switch	47.4	86.6	468	--
Line-haul	38.9	226	558	--
Combined	41.3	187	533	--
SWRI Studies				
GE 12-7FDL[1]				
Switch	106	229	537	40
Line-haul	63	162	403	17
Combined	73	177	433	22
EMD 12-645E3[1]				
Switch	33	104	577	12
Line-haul	18	95	537	12
Combined	22	97	546	12
Best Estimate				
Switch	47.4	86.6	468	40[2]
Line-haul	38.4	226	558	13[3]
Combined	41.3	187	533	20

[1] Calculated by Radian using data from SWRI. These tests were described by Baker et. al., (1984).

[2] Radian estimate, assuming a mix of old and new locomotive engines.

[3] Radian estimate, assuming 80% EMD and 20% GE engines.

To obtain more representative data on railway emissions, the Association of American Railroads (AAR) commissioned measurements on 40 locomotives in the early '80s. Although these data have been released to EPA, they have not been made public, and Radian was unable to obtain access to them. These data, if available, would shed additional light on the question of appropriate gaseous emission factors for locomotives.

Due to the difficulty of building an appropriately-sized dilution tunnel, data on particulate emissions from diesel locomotives are extremely scarce. Our literature survey turned up measurements on only four engines, of which three were conducted at Southwest Research Institute (SWRI). The fourth was made by EMD, using a different procedure, and may not be comparable to the three SWRI measurements.

SWRI performed gaseous and particulate emissions measurements on one EMD 12-645E3 and one GE 12-7FDL engine as part of a study of the effects of heavy blended fuels (Baker et al., 1984). Due to uncertainties in the mass flow measurements, Baker et al. reported the emissions data in terms of concentration, rather than g/BHP-hr. At Radian's request, however, SWRI recalculated the modal emissions data for the baseline tests (using standard diesel #2) to report g/BHP-hr and lb/1000 gallons. From these data, Radian was able to calculate cycle-weighted emission factors for HC, CO, NO_x and particulate matter. The results of these calculations are also shown in Table 4-2; the data and calculations themselves are given in Appendix A.

As Table 4-2 indicates, particulate emissions from the two modern, turbocharged/intercooled locomotive engines tested by SWRI are relatively low compared to other off-highway diesel engines--corresponding to about .26 and .48 g/BHP-hr for the EMD and GE engines, respectively. Earlier SWRI data on an EMD 2-567 engine show considerably higher PM emissions, however (Baker, 1980). These data showed PM emission factors on 39-cetane fuel ranging from 0.7 to 1.25 g/BHP-hr, depending on operating conditions. At the higher BSFC of the

567 engine, these values correspond to about 50-80 lb PM/1000 gallons. Hydrocarbons were also considerably higher, corresponding to about 100 lb/1000 gallons at maximum power.

The 567-series engine used in these tests incorporated older combustion and injection technology, and this is the likely cause of the higher emissions. Substantial reductions in locomotive smoke emissions due to improvements in engine technology have been documented (Kotlin and Williams, 1975). It is also possible that emissions from this laboratory 2-cylinder engine may not have been completely representative of those from actual locomotives.

Our "best-estimate" emission factors for locomotives are shown at the bottom of Table 4-2. For gaseous emissions, the factors for switching and line-haul duty cycles are taken directly from Ingalls (1985). For particulate emission factors, we assumed that virtually all line-haul operation was performed by relatively low-smoke modern locomotives such as the two 12-cylinder engines tested at SWRI. Eighty percent of line-haul operation was assumed to be by EMD locomotives, and 20 percent by GE locomotives.

For switching applications, we assumed that 50 percent of the fuel consumption was by older, high-emitting engines, with the other half split 80 percent to EMD engines and 20 percent to GE engines. The older high-emitting engines were assumed to emit about 60 lb of PM per 1000 gallons of fuel consumed. The resulting composite PM emission factors are 13 lb/1000 gallons for line-haul operation and 39 lb/1000 gallons for switching.

To combine the line-haul and switching-cycle emission factors into one overall factor, the values for the two cycles were weighted by the fraction of fuel consumed in each type of operation--72 percent to line haul and 28 percent switching. These fractions were taken from Ingalls (1985), who used the same fractions to weight emissions of HC, CO, and NO_x in developing his composite emission factor estimates.

4.3 Engine Population and Emissions Inventory

Table 4-3 presents fuel consumption, population, and emissions estimates for diesel-electric locomotives used in switching and line-haul service. These estimates are calculated in two ways: for Class I railroads only; and for all locomotive engines, including those operated by Class II and III Railroads. Class I railroads are those having gross operating revenues of $87.3 million or greater. These railroads account for about 90 percent of all railroad revenues and 97 percent of ton-miles travelled (Assoc. of Am. Railroads, 1986). Class II and III railroads are primarily switching and freight-transfer operations connected with major cities and ports, or short-line operations serving a limited geographic area. Because of their concentration in and near major cities, the Class II and Class III railroads include a disproportionate amount of switchyard operation, and may thus contribute a larger fraction of the urban emissions.

Table 4-3a shows the fuel consumption, locomotive population, and estimated emissions for Class I railroads. The total fuel consumption and population data for this table are taken from the statistics of the Association of American Railroads (1986), and are broken down into line-haul and switching activities following an assumed 72 percent/28 percent split. The AAR fuel consumption data do not include AMTRAK, so we added 60 million gallons for AMTRAK fuel consumption (U.S. Department of Transportation, 1985) to the AAR value. AAR locomotive numbers do include AMTRAK, so no adjustment was necessary. Total emissions were calculated from total fuel consumption using the "best estimate" emission factors from Table 4-2.

Table 4-3b shows estimates of the locomotive population, fuel consumption, and emissions of Class II and III railroads. Locomotive population data for these railroads were obtained by summing the numbers of locomotives reported for these railroads by McDonald (1986). All Class II and Class III railroad locomotives were assumed to operate in a switching cycle, with annual fuel consumption per locomotive equal to that of switchers used by Class I railroads.

TABLE 4-3. POPULATION, FUEL CONSUMPTION, AND ESTIMATED EMISSIONS FOR RAILWAY LOCOMOTIVES

Type	No. Units	Annual Fuel Cons. (1000 Gal.)	Emissions (Tons/Year)[2]			
			HC	CO	NOx	PM
(a) Class I Railroads						
Line-Haul	8,699[2]	2,307,287[3]	44,877	260,723	643,733	14,997
Switch	14,170[2]	897,278[3]	21,265	38,942	209,963	17,946
Total	22,869[1]	3,204,565[1]	66,142	299,665	853,696	32,943
(b) Class II and III Railroads						
Switch	3,236[4]	204,911[2]	4,856	8,893	47,949	4,098
(c) All Railroads						
Line-Haul	8,699	2,307,287	44,877	260,723	643,733	14,997
Switch	17,406	1,102,189	26,122	47,835	257,912	22,044
Total	26,105	3,409,476	70,999	308,558	901,645	37,041
DOE Fuel Cons. Est.[5]		3,209,729				

Sources:

[1] American Association of Railroads, 1986.

[2] Radian estimates.

[3] Calculated from duty cycles in Ingalls (1985).

[4] McDonald, 1986.

[5] Energy Information Admin., 1985.

For comparison, Table 4-3 also shows the DOE estimate of railway fuel deliveries for 1985. This value was based on data obtained from the Association of American Railroads, and thus compares well with the data on Class I railroad fuel consumption taken from AAR statistics.

4.4 Emissions Test Cycle

Since locomotive engines operate in only a few well-defined operating conditions, definition of an appropriate test cycle should be relatively straightforward. The emission factors in Section 4.3 are based on two such test cycles: one for line-haul operation and one for switching. These cycles consist essentially of two different sets of weighting factors for the steady-state emissions measured for each operating mode. Transient effects (if any) are thus ignored. For line-haul operation, this is probably appropriate, as the time spent in notch-to-notch transitions is small compared to the total operating time. Switching duty involves much more transient operation, however, and thus may not be adequately modeled by a steady-state test sequence. This is a concern, since switching and transfer operation are responsible for a large fraction of locomotive emissions in urban areas. Further research to clarify this point is recommended.

In addition to the transient emissions question, the appropriate weighting of different operating modes within each cycle, and of switch versus line-haul operation, should be re-examined in the light of recent changes in operating patterns. Qualitatively, railroads appear to be making more efficient use of equipment, and to be shutting locomotives off more when they will not be used for a some time. Both of these trends should reduce idling time, while increasing the time spent in notches 1-8 and dynamic brake. Ingalls (1985) addressed these issues, but without data to resolve them. Acquisition of actual current operating data would be needed to fully settle this issue.

4.5 Feasibility of Emissions Control

From the data presented in Section 3.2, it is clear that a substantial reduction in locomotive emissions would be possible even with existing technology. With additional R&D in the field, even larger emission reductions could be expected. In this section, we consider two different levels of emissions control for new engines: an intermediate level attainable in the relatively short term (about 3 years), and relying essentially on existing technology; and an advanced level requiring a longer period for research and development. The first of these control levels is intended to be comparable in stringency to EPA's 1988 standards for on-highway diesel engines, while the second is intended to be comparable to the 1991 standards. The reader is warned that these are engineering estimates only, based on very limited data, and intended only to indicate the potential benefits of regulation in this area. Additional research to confirm these estimates would be essential before these or any other emission standards were incorporated into law.

Due to the engine manufacturer's practice of making new-technology components available for rebuilding older engines, much of the emissions-control technology discussed in Section 3.2 would be applicable even to existing locomotives. Thus, in addition to new engines emission levels, estimates of the feasible emissions control level for existing engines are also presented. In most cases, achieving these levels would require rebuilding the engine, at a cost of $80,000 to about $200,000, depending on the extent of the modifications (Davis, 1986). This need not present a major barrier, however. If the engine were being rebuilt anyhow, the additional cost due to the emissions control modifications would be relatively small. Regulations to require best-available control technology on new, rebuilt, or substantially modified locomotives could be reasonable and practical, therefore.

Intermediate level controls--Feasible intermediate-term emission controls for locomotive engines would include retarded injection timing, cooling-system modifications to reduce charge air temperature, increased injection pressure, and optimization of combustion chamber geometry, air flow, and locomotive notch settings for reduced emissions. Based on the data presented in Section 3.2, we estimate that these modifications could reduce NO_x emissions below 6.0 g/BHP-hr.

To ensure against an unacceptable increase in PM and HC emissions at this low NO_x level, a regulatory cap on these emissions would be desirable. Given the limited data available on PM emissions from these engines, the exact PM level achievable at 6.0 NO_x is unknown. However, based on the PM data described above, experience with the on-highway truck standards, and a relatively less stringent steady-state test cycle for locomotives, a PM emissions standard of 0.50 g/BHP-hr appears readily achievable. Based on Table 3-1, an HC emissions standard of 0.50 g/BHP-hr also appears reasonable. The resulting emissions standards and corresponding emission factors are shown in Table 4-4.

Advanced emission controls--Since so little research has been done on medium-speed diesel emissions controls, the ultimate form of advanced emission controls for these engines is difficult to project. Some technologies which clearly could be applied, however, include electronically-controlled unit injectors, reduced oil consumption, higher compression ratios, reduced initial rate of injection, and further optimization of fuel-air mixing and combustion. Vigorous application of these technologies should make possible a further reduction in NO_x emissions to about 4-5 g/BHP-hr, together with lower PM emissions. For this analysis, we assume levels comparable to the 1991 standards for on-highway engines, or 5.0 g/BHP-hr NO_x and 0.20 g/BHP-hr PM.

Levels of emission control well below these limits could conceivably come about through the use of aftertreatment technologies (i.e. trap-oxidizers, catalytic converters, or selective catalytic reduction), alternative fuels (CNG or methanol), water/fuel emulsions and/or exhaust gas recirculation (EGR). EGR in conjunction with a water/fuel emulsion has been shown to be an especially effective emissions control technique for medium-speed engines (Wilson et al., 1982). Further research to establish the effects of these technologies on emissions and durability in actual locomotive engines is required, however.

TABLE 4-4. ESTIMATED ACHIEVABLE EMISSIONS CONTROL STANDARDS FOR LOCOMOTIVE ENGINES

	Emissions Limit (g/BHP-hr)	Equivalent Emission Factor (lb/1000 gal.)
New Engines		
Intermediate Control Level		
NOx	6.00	238
HC	0.50	20
PM	0.50	20
Advanced Technology		
NOx	5.00	198
HC	0.30	12
PM	0.20	8
Existing Engines (retrofit)		
NOx	8.00	317
HC	0.50	20
PM	0.50	20

Source: Radian estimates.

Existing locomotives--Retrofit emission controls for existing locomotives would generally resemble the intermediate-level controls described above. However, not all locomotive models would be equally adaptable to low-emission technologies, so some relaxation of the intermediate-level standards would be desirable for existing engines. We recommend that this relaxation be in the NO_x standard, since over-reducing NO_x can cause large increases in PM and HC emissions and fuel consumption. Research would be required to identify the control levels actually achievable, but a NO_x standard of 8.0 g/BHP-hr should be high enough to avoid any major deterioration in fuel economy or PM emissions.

4.6 Cost-Effectiveness Analysis

Table 4-5 presents some very rough estimates of the cost-effectiveness of controlling locomotive emissions. Two cases are considered: the "intermediate" standards for new engines, and the suggested retrofit standards for existing engines when they are overhauled. Both of these involve relatively near-term technology. The uncertainty in the cost and effectiveness of advanced-technology emission controls is too great to allow for any realistic cost-effectiveness calculations.

Calculation of cost-effectiveness values where more than one pollutant changes poses a difficult cost-allocation problem. The values in Table 4-5 were calculated by allocating all the cost of control to the reduction in HC and NO_x emissions, with no debit for the increase in PM. Reductions in NO_x and HC are often combined in this way, since both pollutants contribute to ozone formation. Since both the "new" and the "existing" engine considered are turbocharged, with relatively modern technology, the major effect of emission controls in each case is a reduction in NO_x, with a minor reduction in HC and a small increase in PM. Application of similar standards to an older (higher PM) locomotive would result in a PM decrease.

TABLE 4-5. ESTIMATED COST-EFFECTIVENESS OF EMISSIONS CONTROL FOR NEW RAILWAY LOCOMOTIVES

	New Engine	Existing Engine
EMISSION CONTROL COSTS		
Initial Cost	$ 80,000	$100,000
Engine Life (yrs)	15	7
Amortized Cost/year @ 10%	$ 10,518	$ 20,541
Fuel Cons. Increase	5%	3%
Annual Fuel Cons. (Gal)		
Baseline	138,000	140,680
With controls	144,900	144,900
Added Fuel Cost @ $0.80/gal	$ 5,520	$ 3,376
Addl. Ann. Maintenance	$ 5,000	$ 5,000
Annualized Control Cost Per Locomotive	$ 21,038	$ 28,917
EMISSIONS		
Emission Factors (lb/1000 gal.)		
Baseline		
NOx	523	533
HC	32	41
PM	14	20
With Controls		
NOx	238	238
HC	20	20
PM	18	20
Annual Emissions (tons/locomotive year)		
Baseline		
NOx	36.1	37.5
HC	2.2	2.9
PM	1.0	1.4
With Controls		
NOx	17.2	17.2
HC	1.4	1.4
PM	1.3	1.4
Emissions Reduction (tons/locomotive year)		
NOx	18.8	20.2
HC	0.8	1.5
PM	-0.3	0.0
Cost-Effectiveness ($/ton)		
NOx + HC	$ 1,073	$ 1,332

The data in Table 4-5 are based on rather high estimates of the costs of meeting emissions standards for medium-speed engines. These reflect the great cost of the engines themselves, the small sales volume (resulting in a greater cost per engine for development and certification), and the small amount of existing work on medium-speed engine emission controls. These values are considered to be somewhat conservative (in the sense of over-stating the cost of control)--actual costs per unit might well be less, but are considered unlikely to be significantly more. Despite this, the estimated costs-per-ton of NO_x + HC controlled are rather low compared to most other significant new source of NO_x reductions. Thus, imposition of intermediate-technology emission standards both on new locomotives and on existing locomotives when they are rebuilt should be a highly cost-effective emissions control strategy.

5.0 MARINE VESSELS

Marine vessels included in this study include diesel-powered tug and towboats, passenger vessels, fishing vessels, and private recreational craft, but not ocean-going ships. Worldwide, the vast majority of ocean-going ships (as well as most smaller non-recreational vessels) are now diesel powered, due to the superior fuel efficiency of the diesel engine. These ships are doubtless significant contributors to the emissions inventories in major port cities such as Los Angeles or New York. For historical reasons, however, few U.S.-flag ships are diesel powered. Access of foreign-registered ships (including motorships) to U.S. ports is controlled by treaty, and would thus not be subject to regulation by EPA, even if other off-highway vehicles were made subject to such regulations.

5.1 Engine Characteristics and Operating Conditions

Except for those used in oceangoing ships, the diesel engines used in marine vessels are primarily high-speed engines from Groups 2 and 3, or medium-speed engines classed in Group 1. High-speed engines are used as the main propulsion in smaller craft, and for electric generation on larger vessels. Vessels such as pleasure craft, fishing boats, small workboats, and similar vessels are typically powered by Group 2 engines similar to those used in highway trucks. The larger Group 3 engines are used in many tugboats, towboats, and similar vessels.

Many of the smaller high-speed marine engines in use are naturally-aspirated, and the turbocharged ones may or may not be equipped with intercoolers. Most of the more powerful Group 2 engines and most Group 3 engines in marine applications are turbocharged and aftercooled, however. To increase power output still further, some engines in this group use low-temperature aftercooling, cooling the heat exchanger with water pumped from overside. However, many engines in this class still use jacket water aftercooling, due to the possible corrosion problems involved (especially with sea-water).

Most high-speed diesel engines in marine service in the U.S. were built by Detroit Diesel Allison, Caterpillar, or Cummins. The majority of these engines are equipped with direct injection combustion systems, and most use unit injectors. IDI engines in marine use include the Caterpillar 300-series and a few light-duty engines used mostly in pleasure craft. The 300-series IDI engines have been superseded in Caterpillar's product line by the direct-injected 3500 series. They were extremely popular marine engines, however, and many remain in use.

Main propulsion for most large, powerful working vessels such as large tugboats, river towboats, and offshore oil supply vessels is provided by locomotive-derived medium-speed engines such as the EMD 567 and 645 series and Alco locomotive engines. These engines are identical in every major respect to the similar-model engines used in locomotives. Still larger medium-speed engines, specifically designed for marine service, power Great Lakes freighters and similar vessels, including many oceangoing ships. Slow-speed diesel engines are used only in large ocean-going ships, where their very low rotational speed allows them to be direct-coupled to the propeller. As this report does not deal with ocean-going ships, slow-speed engines will not be discussed further.

High-speed and medium-speed diesel engines used for vessel propulsion are normally coupled to the propellers through a set of reducing gears or "marine transmission", which provides forward and reverse motion, but only one reduction ratio. The engine speed is thus a constant multiple of the propeller speed, while the engine power output is determined by the propeller's power absorption curve. The vessel's helmsman controls the engines through a set of "throttles", which change the engine speed setpoint of a constant-speed governor. For a given "throttle" position, therefore, the engine RPM (and thus propeller RPM) is held constant, and the governor adjusts engine power output as needed to maintain this RPM setting.

Propeller power absorption increases as the cube of the rotational speed. Thus, if the engine and propeller are properly matched, maximum engine power is produced only near the engine's rated speed, and the power required drops off rapidly as RPMs are reduced. Much of the engine's operating time, and most of the BHP-hr produced occur in "cruise" mode. Typical "cruise" RPM is about 80-95 percent of rated speed, corresponding to about 40-80 percent of maximum power. Like locomotive engines, marine engines also spend a great deal of time idling. This is due to the inconvenience of starting large diesel engines when cold, and to the need to have engine power available at short notice under many conditions.

In addition to their main propulsion engines, larger marine vessels use smaller, high-speed diesel engines to drive generators for electrical power. These engines (typically Class 2 or Class 4) are governed at synchronous speed, which is normally 1,800 RPM for U.S. vessels. To provide electric power as needed, they generally run continuously, even when the vessel is docked, moored, or otherwise temporarily inactive. Since these engines are sized to handle the maximum expected electric power demand, they run most of the time under rather light load. Unlike engines used for main propulsion, generator engines tend to be naturally aspirated, and have relatively high NO_x emissions as a result.

5.2 Current Emission Factors

Reliable emission factors for marine vessels equipped with either high or medium-speed engines are unavailable. While emission factors for these vessels are listed in EPA's AP-42 compilation of emission factors, a review of the derivation of these factors (Ingalls, 1985) showed that they were computed incorrectly, and that they are based on a narrow range of engines which is no longer representative of those in use. In addition, AP-42 provides no data on particulate emissions from marine engines. Thus, we were forced to develop our own estimates of emission factors for high-speed and medium-speed diesel engines in marine use.

The emission factors developed in this report are intended to represent composite emissions over the entire engine duty cycle, for a broad range of engine horsepower ratings. AP-42, on the other hand, presents separate emission factors for each operating mode, and divides them into a number of rather narrow horsepower ranges. For these reasons, no direct comparison of the Radian and AP-42 emission factors is possible.

The great majority of medium-speed diesel engines in marine use in the U.S. are essentially seagoing locomotive engines. Since the emission factors for locomotives are reasonably well defined, and since the duty cycle for marine engines is not too dissimilar from that of locomotives, it was decided to apply the "best estimate" emission factors developed for locomotives to medium-speed marine engines as well. These factors (which are listed in Table 5-1) are the same as the composite of the line-haul and switching duty cycles listed in Table 4-3.

Emission factors for high-speed diesel engines in marine service are also listed in Table 5-1. These values are Radian estimates, based in part on the data used in developing the AP-42 emission factor estimates (Engineering Science, 1984) and partly on other data sources (Dowdall, 1987; Santa Barbara APCD, 1987). The particulate emissions factors were based primarily on measurements in uncontrolled heavy-duty truck engines, (Weaver, et. al., 1984) which may not be fully applicable in this case. All of the factors shown should be considered only very rough approximations--acquisition of better data through actual testing is strongly recommended.

TABLE 5-1. ESTIMATED CURRENT EMISSION FACTORS FOR DIESEL ENGINES USED IN MARINE APPLICATIONS

	EMISSION FACTORS	
	g/BHP-hr	lb/1000 gal.
High Speed Engines[1]		
HC	0.8	32
CO	3.0	119
NOx	11.0	436
PM	0.6	24
Medium Speed Engines[2]		
HC	1.0	41
CO	4.7	187
NOx	13.4	533
PM	0.5	20

Sources:

[1] Radian estimate.

[2] From Table 4-2.

5.3 Engine Population and Emissions Inventory

Table 5-2 lists the estimated population and nationwide fuel consumption data for the major classes of diesel powered, non-oceangoing vessels in use in the U.S. These estimates should be understood as being very approximate--data on marine vessel populations and usage in the U.S. are fragmented, incomplete, and occasionally contradictory. Table 5-2 was patched together from 9 independent sources. We relied most heavily on the Army Corps of Engineers Summary of U.S. Flag Passenger and Cargo Vessels (Army Corps of Engineers, 1983). This report does not include all relevant vessels, however. Data on the number of fishing and pleasure craft were obtained from other sources.

The breakdown of the total horsepower shown in Table 5-2 into high-speed and medium-speed engines is based on only very limited data. Descriptions of the engines and horsepower ratings for tug and towboats are given in the Inland River Record (Owen, 1986). Analysis of a sample of these boats showed that only 20 to 25 percent of these boats are powered by medium-speed engines, but that these engines are responsible for about 60 percent of the total horsepower for the group. Extrapolating from this limited information, we estimated that about 60 percent of dry cargo and/or passenger ship horsepower, 50 percent of ferry horsepower, and 20 percent of commercial fishing craft (over five tons) horsepower are generated by medium speed engines.

Table 5-2 shows an estimate of the total annual fuel consumption by each class of marine vessels. These were calculated from the engine load factors and annual usage shown in the table, and an assumed fuel consumption of 0.4 lb/BHP-hr. The load factors and annual usage values shown are Radian estimates, based on typical operating patterns for each class. These values are only rough approximations, as actual data on load factors and hours of operation are lacking.

TABLE 5-2. ESTIMATED NATIONWIDE POPULATION AND EMISSIONS FROM DIESEL ENGINES USED IN MARINE APPLICATIONS

	Diesel Vessels	Total Horsepower (1000s)	Load Factor[1]	Usage (Hr/Yr)[1]	Ann. Fuel Consumption (1000 gal)	EMISSIONS (TONS/YR) HC	CO	NOx	PM
Dry Cargo/Passenger	1,893[1,2,3,4]	5,494			457,833	8,561	36,581	113,131	4,945
High-Speed		2,198	50%	3,000	183,133	2,930	10,896	39,923	2,198
Medium-Speed		3,296	50%	3,000	274,700	5,631	25,684	73,208	2,747
Towboats and Tugboats	5,418[1,2]	7,988			798,800	15,177	65,635	199,966	8,521
High-Speed		3,195	50%	3,000	266,267	4,260	15,843	58,046	3,195
Medium-Speed		4,793	50%	4,000	532,533	10,917	49,792	141,920	5,325
Railroad Ferries	107[1]	262			11,644	223	970	2,934	123
High-Speed		79	40%	2,000	3,493	56	208	762	42
Medium-Speed		183	40%	2,000	8,151	167	762	2,172	82
General Ferries	1,000[1,2]	1,000			44,444	811	3,400	10,767	489
High-Speed		500	40%	2,000	22,222	356	1,322	4,844	267
Medium-Speed		500	40%	2,000	22,222	456	2,078	5,922	222
Fishing Craft	115,800[5,6]	24,400			423,333	7,133	27,908	96,167	4,920
> 5 Net Tons	24,000[5,6]	12,000			320,000	5,480	21,760	73,640	3,680
High-Speed		9,600	30%	1,500	240,000	3,840	14,280	52,320	2,880
Medium-Speed		2,400	30%	2,000	80,000	1,640	7,480	21,320	800
< 5 Net Tons									
High-Speed	91,800[5,6]	12,400	30%	500	103,333	1,653	6,148	22,527	1,240
Pleasure Craft									
High-Speed	97,000[1,7]	17,500	50%	200	97,222	1,556	5,785	21,194	1,167
Total	221,218	56,644			1,833,278	33,462	140,279	444,158	20,164
High-Speed	218,718	45,471			915,671	14,651	54,482	199,616	10,988
Medium-Speed	2,500	11,173			917,607	18,811	85,796	244,542	9,176
DOE Fuel Cons. Estimate					1,894,265				

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[1] Radian estimate.
[2] Including an estimate of unreported craft (Crowell, 1986).
[3] U.S. Army Corps of Engineers, 1983.
[4] U.S. Maritime Administration, 1983.
[5] National Marine Fisheries Service, 1984.
[6] John O'Donnell, 1986.
[7] Moyat, 1986.

Total fuel consumption by all classes shown in the table is approximately 1.8 billion gallons per year. A DOE report (Energy Information Administration, 1985) showing the total consumption of distillate fuel oil for vessel bunkering at about 1.9 billion gallons, served to calibrate our estimate. The two numbers are not strictly comparable, since the DOE value includes distillate fuel consumed by oceangoing ships. These ships burn primarily residual fuel oil, but some use a certain percentage of distillate fuel oil as well. This is offset to some degree by the fact that some non-oceangoing vessels can use residual oil or distillate/residual blends.

One other source of information on marine fuel consumption was located. Based on the results of a national freight transportation model, Argonne Laboratory (Millar et al., 1982) estimated total energy consumption for tugs and towboats in the U.S. at about 147 trillion BTU, or slightly over 1 billion gallons of diesel fuel equivalent. Even considering that this value includes some non-diesel energy consumption, this is somewhat higher than the estimates in Table 5-2.

Estimates of pollutant emissions from the various types of marine vessels are also presented and totaled in Table 5-2. These estimates were arrived at by multiplying the emission factors in Table 5-1 by the fuel consumption data calculated in Table 5-2.

In terms of regional distribution, 55 percent of dry cargo and/or passenger ships are located on the Mississippi and Ohio Rivers, 35 percent along the U.S. coastline, and the rest are situated on the Great Lakes. A considerably different situation exists for railroad ferries where 90 percent are located on the coastline with the remainder on the Great Lakes. For towboats and tugboats, the percentages are 31 percent, 66 percent, and 3 percent for the coastal areas, inland waterways, and Great Lakes, respectively (U.S. Army Corps of Engineers, 1983). These these statistics indicate that a large percentage of domestic vessels operate on the Mississippi and Ohio

Rivers. Since the Mississippi and Ohio Valleys and lower Great Lakes region are one of the densest clusters of urbanized areas in the United States, the impact of these emissions on humans could be significant.

Fishing and pleasure craft, on the other hand, are located predominately along the U.S. coastline. The only major inland concentration of fishing craft is on the Chesapeake Bay, which accounts for 21 percent of fishing craft (National Marine Fisheries Service, 1984). Likewise, most inboard pleasure craft are operated on the coasts with the Great Lakes being the only major inland concentration. About 25 percent of these boats are operated on the great lakes (Cmdr. Scarborough, 1986).

5.4 Emissions Test Cycle

Relatively little investigation of marine engine duty cycles has been performed. From the few studies which have been done (e.g., Santa Barbara APCD, 1987), as well as discussion with vessel operators, it is clear that most of the fuel burned in marine operations is burned in cruise mode, with vessel maneuvering and idle making fairly minor contributions. Idle does account for a very significant fraction of the operating time, however, which suggests that it could be an important contributor to HC and PM emissions. Full-speed, full-load operation may also contribute significantly to PM emissions, since some vessels "cruise" at full power. Due to the dominance of steady-state operating modes, transient effects on emissions are probably negligible.

These facts suggest that an appropriate test cycle for marine propulsion engines could consist of four steady-state operating modes: idle, light load/low RPM, "cruise", and full load, with cruise and idle weighted most heavily. For generator engines, a single-speed, multi-power level test cycle (e.g. 2, 25, 50, 75, and 100 percent load at 1800 RPM) would give the most realistic representation of in-use conditions.

5.5 Feasibility of Emissions Control

Estimates of achievable emission standards for diesel engines used in marine applications are shown in Table 5-3. For new engines, two levels of emissions control are considered. The "intermediate" control level is intended to correspond in stringency to the 1988 on-highway emissions standards, while the "advanced technology" level corresponds to the standards scheduled for 1991. In addition, Table 5-3 shows our estimates of achievable retrofit emission control standards for existing medium-speed and large high-speed engines. Again, the reader is warned that these are engineering estimates only, based on very limited data, and intended only to indicate the potential benefits of regulation in this area. Additional research to confirm these estimates would be essential before these or any other emission standards were incorporated into law.

High speed engines

Intermediate control level--High-speed engines are used both for propulsion and as prime movers for electric generation. Although the duty cycles for these two types of operation vary somewhat, the applicable emission control technologies are essentially the same. At the intermediate control level, these technologies include: turbocharging with low-temperature aftercooling; increased boost pressure; retarded injection timing (with timing advanced at light loads to reduce HC and PM emissions); and changes in airflow, fuel injection, and combustion chamber design to minimize emissions. These technologies have all been well demonstrated in on-highway engines, and the combination of high boost pressure with low-temperature aftercooling has seen increasing use in marine main propulsion engines as well. Application of these technologies across the board should be straightforward, therefore. The emissions levels achievable with these technologies should be comparable to the 1988 standards for on-highway diesels. This is reflected in Table 5-3.

TABLE 5-3. ESTIMATED ACHIEVABLE EMISSIONS CONTROL STANDARDS FOR MARINE DIESEL ENGINES

	Emissions Limit (g/BHP-hr)	Equivalent Emission Factor (lb/1000 gal.)
HIGH-SPEED MARINE ENGINES		
Intermediate Control Level		
NOx	6.00	238
HC	0.50	20
PM	0.50	20
Advanced Technology		
NOx	5.00	198
HC	0.50	20
PM	0.25	10
Existing Engines Over 300 HP (retrofit)		
NOx	8.00	317
HC	0.50	20
PM	0.50	20
MEDIUM-SPEED MARINE ENGINES		
Intermediate Level		
NOx	6.00	238
HC	0.50	20
PM	0.50	20
Advanced Technology		
NOx	5.00	198
HC	0.30	12
PM	0.20	8
Existing Engines (retrofit)		
NOx	8.00	317
HC	0.50	20
PM	0.50	20

Source: Radian estimates.

Advanced technology--The list of possible advanced emission control technologies for marine engines is essentially the same as the list of intermediate control technologies, with the possible addition of electronic timing controls. Exhaust gas recirculation would probably be ruled out for marine engines, due to its possible impact on engine reliability; while catalysts and trap-oxidizers would likely be ruled out by fire-safety considerations. The emissions standards in Table 5-3 reflect these limitations. The PM level of 0.25 g/BHP-hr shown for the "advanced technology" standards--while numerically identical--is actually somewhat more lenient than the 1991 PM standard for on-highway vehicles. This is due to the fact that PM for marine vessels would be measured in steady-state operation, while the on-highway standard is based on a highly transient operating cycle.

Retrofits--As with locomotive engines, high-horsepower marine engines are commonly upgraded to current technology levels when they are overhauled, and they can achieve an indefinite lifespan through repeated overhauls. Thus, as with locomotives, it would make sense to consider requiring retrofit of emissions controls to these engines. The major changes required would be the pistons, injectors, and camshafts, (most or all of which would be replaced in any event), plus possible changes in the turbocharger and aftercooler system. Since the engine would already be dismantled for overhaul, the added cost of these changes would be relatively small. For cost-effectiveness reasons, it would be desirable to limit this requirement only to the larger engines, which tend to see more intensive use. For our purposes, we have drawn the line arbitrarily at 300 HP, but further research to determine an appropriate level is recommended.

Medium-speed engines

The estimates of achievable emissions control levels for medium-speed engines in marine service are identical to the estimates previously presented for locomotive engines. The modifications required to these engines would also be essentially the same as those required for locomotive engines: upgrading engine components, retarding injection timing, increasing the injection rate, and modifying the engine cooling system to provide low-temperature aftercooling. Due to the availability of the ocean as a heat sink, this last modification would be easier and less expensive for marine engines than for locomotive engines.

5.6 Cost-Effectiveness Analysis

Table 5-4 shows some very rough calculations of the cost-effectiveness of emissions control to the "intermediate" level for new diesel engines of three types: medium-speed and high-speed main propulsion engines, and a high-speed generator engine. While they are very rough and approximate, these calculations give some idea of the potential cost-effectiveness of controlling these engines, compared to other sources of potential emission reductions. As with locomotives, cost-effectiveness is calculated based on the reduction in NO_x and HC emissions, and no credit or penalty is taken for PM emission changes. No cost-effectiveness estimates were made for "advanced technology" emission controls or for retrofits, due to the uncertainty (and, for retrofits, the great variability) of costs in these cases.

For the medium-speed engine, the costs of emission control assumed in these calculations are less than those assumed for a similar engine in locomotive service. This is due primarily to the lower costs assumed for the low-temperature aftercooler. In a locomotive, this would require an air-air aftercooler or a large separate air-water heat exchanger, either of which would be difficult to engineer into the limited space available. In marine operation, an effectively infinite heat sink is available in the water close overside, so that the cost of low-temperature aftercooling would be relatively small. Maintenance costs would also be lower, due to the absence of the air-air heat exchanger and the less intensive use. The other costs assumed for this intermediate control level are primarily design, development, and

TABLE 5-4. ESTIMATED COST-EFFECTIVENESS OF EMISSIONS CONTROL FOR DIESEL ENGINES USED IN MARINE APPLICATIONS

	Main Propulsion Engines		
	Medium-Speed	High-Speed	Generator Engine
EMISSION CONTROL COSTS			
Engine Horsepower	2,500	500	200
Initial Cost	$50,000	$3,000	$1,000
Engine Life (yrs)	20	15	15
Amortized Cost/year @ 10%	$5,873	$394	$131
Fuel Cons. Increase	5%	5%	5%
Annual Fuel Cons. (Gal)			
Baseline	160,000	12,500	16,000
With controls	168,000	13,125	16,800
Added Fuel Cost @ $0.80/gal	$6,400	$500	$640
Addl. Ann. Maintenance	$3,000	$200	$200
Annualized Control Cost Per Engine	$15,273	$1,094	$971
EMISSIONS			
Emission Factors (lb/1000 gal.)			
Baseline			
NOx	523	436	436
HC	32	32	32
PM	14	24	24
With Controls			
NOx	238	238	238
HC	20	20	20
PM	18	20	20
Annual Emissions (pounds per engine per year)			
Baseline			
NOx	83,680	5,450	6,976
HC	5,120	400	512
PM	2,240	300	384
With Controls			
NOx	39,984	3,124	3,998
HC	3,360	263	336
PM	3,024	263	336
Emissions Reduction (pounds per engine per year)			
NOx	43,696	2,326	2,978
HC	1,760	138	176
PM	(784)	38	48
Cost-Effectiveness ($/ton)			
NOx + HC	$672	$888	$616

certification costs, which (while large) would be spread over a large number of marine and locomotive engines. The additional manufacturing costs of refinements in injectors, combustion chambers, injection timing, etc. are relatively small.

For the two high-speed engines, the approximate emission control costs shown were based on existing technology for on-highway truck engines. Technologies assumed were: turbocharging (for engines that don't have it already), low-temperature aftercooling, retarded injection timing, increased boost pressure, and optimization of combustion chamber and injector characteristics. The major costs in this package are for the turbocharger and aftercooler, and the design and certification costs for the engine. These were assumed to be fairly high, as the marine market is limited, and Coast Guard and American Bureau of Shipping regulations pose a formidable barrier to new technologies.

As Table 5-4 indicates, the potential cost-effectiveness of emissions control for new marine engines is about $600-$900 per ton. This is quite attractive when compared to the costs per ton for other available NO_x and HC reductions.

6.0 FARM EQUIPMENT

Self-powered farm equipment includes tractors, combines, mowers, and other self-propelled machinery used in agriculture. For the last 20 years, the engines used in these vehicles have been overwhelmingly diesel, and they are responsible for most diesel fuel consumption on farms. Engines in non self-propelled equipment such as irrigation pumps, engine-driven blowers, conveyors, etc. are responsible for a relatively small fraction of total fuel consumption and emissions, and are not discussed here.

6.1 Engine Characteristics and Operating Conditions

The largest group of agricultural diesel engines are those used in tractors. Tractor engines tend to be naturally-aspirated, direct-injected, 4-stroke engines of moderate speed and power output (15-180 HP) and four to six cylinders. Engines used in small utility tractors are primarily Group 4 engines of 15-50 HP and Japanese manufacture. Similar engines are also used in lawn and garden equipment. Larger tractor engines in the 40-180 HP range are often produced by the tractor builder, and are specifically designed for tractor use. In addition to supplying motive power, these engines are often an integral part of the structural framework of the tractor, with specially reinforced oilpans and engine blocks to carry the structural load. These engines are classed in Group II, and a number of them have been adapted for use (in a non-structural role) in highway trucks as well. Examples include the John Deere 300 and 400-series engines and the Ford 6-cylinder diesel engines.

Recent years have shown an increasing trend to higher tractor power rating and tractors of 400 HP and above are now available in four wheel drive tractors. These high-powered engines are generally adapted from those used in on-highway trucks, and are often turbocharged and intercooled for increased output (Implement and Tractor, 1986). Truck-type engines have also seen increasing use in smaller tractors, with makers such as Perkins and Isuzu supplying engines to tractor makers such as Massey Ferguson and White.

Tractors undergo a varied and rigorous duty cycle. In addition to plowing, planting, cultivating, hay baling, and other heavy agricultural work, tractors are used for mowing, pulling wagons, front-end loading, driving fence posts, blowing snow, bulldozing, and even light earthmoving jobs. The smaller utility tractors, as their name implies, tend to see a greater variety of applications, while the larger and more powerful tractors are primarily used for heavy field work.

Combines, windrowers, cotton pickers, and other specialized non-tractor agricultural equipment undergo a less varied duty cycle. Engines for these vehicles are often equipped with medium-heavy duty truck engines such as the Navistar DT 466 and the Caterpillar 3208. These may be naturally-aspirated or turbocharged. In other cases, adaptations of tractor engines or (in a few cases) specially-designed engines are used.

A weighted average of Harvest Publishing's 1985 Tractor Survey, the largest number of tractors in use were made by John Deere and International Harvester, both of which had produced about approximately 27 percent of the total. Other significant tractor manufacturers include Massey Ferguson, Ford, Allis-Chalmers, White, and J.I. Case, all of whom had produced from 7 percent to 10 percent of the tractors in use. Historically, John Deere, International, Ford, and Case have produced their own tractor engines, while Massey Ferguson, Allis, and White tend to use purchased engines.

The agricultural equipment operations of J.I. Case and International Harvester were recently merged, and new tractors produced by Case-IH will presumably be designed around the "B" and "C" engines produced by Case and Cummins in a joint venture arrangement. These engines are also targeted for the light-heavy and medium-heavy truck markets.

6.2 Current Emission Factors

The best data on emission factors for farm equipment are contained in a report to the California Air Resources Board by Environmental Research and

Technology (ERT) (1982). This report was sponsored by the farm equipment, construction equipment, and engine industries through their respective associations, and summarizes massive amounts of manufacturer-supplied data. Although the report deals specifically with California, the emission factor data contained in it are the best available for remainder of the U.S. as well. These data are presented in Table 6-1.

The data in the ERT report suffer from several limitations. The most important of these is the absence of particulate measurements. As a result, the PM emission factors in Table 6-1 were taken from AP-42 (EPA, 1985). These factors are based on emissions measurements on a limited sample of farm and construction equipment engines tested at Southwest Research in the early 70's (Hare et al., 1975). In comments on our Task One interim report, the Engine Manufacturer's Association (EMA) criticized our use of these factors, stating that they are no longer representative of farm and construction equipment today (Young, 1987). This criticism has some validity, especially for the larger truck-derived engines used in higher-powered equipment. No examples of these engines were tested in the SWRI program, and it is not clear that the emission factors developed for the smaller engines are appropriate here. As a result, we have substituted a value of 0.80 g/BHP-hr (based on pre-control particulate emissions from heavy-duty truck engines) for the EPA emission factor for four-wheel drive tractors.

For two-wheel drive tractors and other agricultural equipment, we elected to retain the EPA emission factors. While it is true that many of the specific engine models tested by Hare et al. are no longer in use, there is little evidence to suggest that the new engines that replaced them are any cleaner, and no more recent emissions data are available. Research to obtain more recent and applicable emissions data is strongly recommended.

Another limitation of the ERT data is that they are based on an adaptation of the old 13-mode steady-state test cycle, and thus do not account

TABLE 6-1. EMISSION FACTORS FOR FARM EQUIPMENT

	EMISSION FACTORS (G/BHP-HR)			
	HC[1]	CO[1]	NOx[1]	PM[2]
Equipment Type				
Tractor, 2WD 100+ HP	1.84	4.23	11.59	1.28
Tractor, 4WD	0.89	3.28	10.98	0.80[3]
Tractor, 2WD, 20-90 HP	2.16	6.42	10.94	1.28
Combines, Self-propelled	1.90	3.25	13.36	1.51
Windrower, Self-propelled	2.21	6.85	10.50	1.51
Field Forage Harvesters	0.96	2.84	9.98	1.51
Cotton Pickers	2.23	3.78	7.78	1.51
Cotton Sprayers	2.23	3.78	7.78	1.51
Orchard Sprayers	2.23	3.78	7.78	1.51
Compact Loaders	1.13	4.29	9.69	1.51
Fuel-Weighted Emission Factors				
lb/1000 gal	72	182	456	50
g/BHP-hr	1.81	4.59	11.50	1.25

Sources:

[1] ERT, 1982.

[2] EPA, AP-42, 1985.

[3] Radian estimate.

for any transient effects. This is also true of the PM data developed by Hare et al. This is not a problem for most categories of farm equipment, since combines, windrowers, large tractors, etc. tend to be used primarily in nearly steady-state operation. It may be a problem for the smaller tractors, however, as these units tend to experience a fair amount of cyclic operation, and it is certainly a problem for the compact loaders. This issue is discussed further in Section 6.4.

Table 6-1 also shows a set of "fuel weighted" emission factors for farm equipment. These are simply the average of the emission factors for each equipment class, with each class' contribution weighted by its estimated fraction of total diesel fuel consumption by farm equipment. The estimates of diesel fuel consumption by each class are shown in Table 6-2.

6.3 Engine Population and Emissions Inventory

Reasonably complete information on farm equipment populations and emission characteristics is available. Population data are available in numerous statistical summaries of the agriculture sector, and in estimates developed by the Farm Implement and Equipment Institute, the industry association. Table 6-2 shows our estimates of total populations, usage, fuel consumption, and emissions for the major classes of self-propelled farm equipment. These estimates are based on FIEI revisions to USDA population numbers, and to the ERT estimates of average horsepower and hours of usage per year (Young, 1987). As the table indicates, the great bulk of agricultural equipment emissions--accounting for about 85 percent of the total--are due to tractors, with combines the only other major source.

Table 6-2 includes an estimate of the total nationwide fuel consumption by agricultural equipment, calculated from the FIEI data and assuming fuel consumption of 0.4 lb/BHP-hr. Also shown in the table is the Department of Energy's estimate of total distillate fuel deliveries in the agricultural sector for 1985. This value is closely comparable to the value calculated from the FIEI data.

TABLE 6-2. ESTIMATED POPULATION, FUEL CONSUMPTION, AND EMISSIONS FROM DIESEL ENGINES USED IN FARM EQUIPMENT

Equipment Type	Total Population[1]	Pcnt. Diesel[2]	Diesel Population	Usage (hr/yr)[3]	Avg. H.P.[3]	Load Factor[3]	Annual Fuel Consumption[4] (1000 Gal)	EMISSIONS (TONS/YEAR) HC	CO	NOx	PM
Tractor, 2WD 100+ HP	865,700	94%	813,758	410	141	0.55	1,437,438	52,432	120,536	330,262	36,474
Tractor, 4WD	85,475	100%	85,475	530	227	0.84	365,635	6,451	23,774	79,586	5,799
Tractor, 2WD, 20-90 HP	3,597,501	70%	2,518,251	300	56	0.34	799,125	34,218	101,704	173,308	20,277
Combines, Self-propelled	500,000	75%	375,000	220	136	0.58	349,067	13,148	22,489	92,449	10,449
Windrower, Self-propelled	110,000	20%	22,000	418	75	0.55	21,074	923	2,882	4,387	631
Field Forage Harvesters	9,500	100%	9,500	390	150	0.78	24,083	458	1,356	4,765	721
Cotton Pickers	20,000	70%	14,000	353	115	0.55	17,366	768	1,301	2,678	520
Cotton Sprayers	2,700	70%[5]	1,890	230	95[5]	0.50	1,147	51	86	177	34
Orchard Sprayers	20,629	10%	2,083	100	70	0.35	281	12	21	43	8
Compact Loaders	113,400	23%	26,082	320	37	0.37	6,348	142	540	1,219	190
TOTAL			3,868,019				3,021,561	108,603	274,869	888,874	75,103
DOE/EIA Fuel Cons. Estimate							3,161,338[6]				

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[1] FIEI adjustments to USDA (1985) (Young, 1987).
[2] FIEI estimates (Young, 1987).
[3] FIEI adjustments to ERT (1982).
[4] Calculated assuming fuel consumption of 0.4 lb/BHP-hr.
[5] Radian estimate.
[6] Energy Information Admin., 1985.

Almost by definition, farm equipment emissions are concentrated in rural areas. Although some farming often occurs even in highly urbanized regions, such as the South Coast Air Basin of California, diesel farm equipment for only 0.25 percent of the NO_x inventory in the SCAB. For comparison, in the heavily agricultural Fresno area (which, like the SCAB, is not in attainment of the Federal ozone standards) diesel farm equipment accounts for about 6 percent of the NO_x inventory. These estimates were obtained by adjusting similar figures for gasoline and diesel-powered equipment (Ingalls, 1985) to reflect only diesel engine-powered equipment.

Using regional sales figures from the July 1985, Petroleum Marketing Monthly (EIA, 1985), a good national distribution of farm equipment emissions can be determined. It should be recognized that this distribution is based on the premise that agricultural sector fuel sales and engine emissions are similarly related in all regions of the country. Using this tack, the New England states account for .4 percent of farm related emissions, Mid-Atlantic states account for 2.8 percent and, the rest of the eastern seaboard states make up 8.4 percent. The Midwest accounts for a lion's share 49.2 percent of farm generated pollutants. The South and Northwest add another 16.7 percent and 6.0 percent, respectively, to the farm emissions total. Finally, the West is responsible for the remaining 16.5 percent.

6.4 Emissions Test Cycles

As noted in Section 6-2, most types of self-propelled farm equipment are used in essentially steady-state operation. For combines and other specialized equipment, the engine generally experiences only a very limited range of operating conditions. For tractors, the range of operating conditions is larger, varying from high-speed, low load running in light tasks to sustained near-full power output in heavy work. For most tasks, however, the engine speed and power requirements do not vary greatly from second to second, so that a steady-state test cycle would probably be adequate for measuring emissions. Although tractors in field operation do experience some cyclic operation (when turning at the end of a row, for instance) these cycles are long enough that the transient effects would probably be negligible. However, transient emissions measurements (using a realistic cycle) on actual tractor engines would be desirable in order to confirm this assumption.

An exception to the general rule of steady-state operation would occur in the case of compact loaders; and of tractors used for utility work (such as front-end loading) which involves repeated short-cycle operation. For these units, some sort of cyclic, transient duty cycle, similar to the construction equipment test cycles discussed in Section 7.3, might be more appropriate. At this point, the actual extent and emissions effects of cyclic operation in smaller tractors are unclear, and further research to resolve this question is recommended.

6.5 Feasibility of Emissions Control

As noted above, most tractor and other agricultural equipment engines are classed in Group 2, with the remainder being classed in Group 4. As both of these engine groups are closely related to on-highway engines, most emission control technologies developed for on-highway use should be readily adaptable. The differences in duty cycle, application requirements, and environmental conditions between the two types of applications will impose some limitations, however. In particular, the close integration of the engine and the equipment in tractors, loaders, and some other equipment types could result in delays or large economic penalties due to the adoption of emission controls.

Tractors, loaders, and (to a lesser extent) other farm machines are literally designed around the physical dimensions and operational capabilities of the engine. The physical dimensions of the engine determine the location of the tractor's hood and frame, and any changes to these dimensions may require redesign of major portions of the structure. In the same way, gear and final drive ratios, hydraulic system characteristics, and other design variables are determined by the torque/speed characteristics of the engine, and any major changes in these characteristics may involve major expense.

Unlike passenger cars, which undergo major design changes every few years, farm equipment designs have a rather long life cycle. The economic life of a tractor or combine design is of the order of ten years, after which the unit will be completely re-engineered and re-tooled. At any given time, some portion of a manufacturer's product line is undergoing this re-engineering, so that each manufacturer typically brings out some new equipment designs each year.

To avoid undue financial and engineering burden on the industry, it would be desirable to incorporate any major changes required for emissions control in new models as they are redesigned, rather than imposing a single requirement across the board. One approach to implementing this requirement would be through an averaging, trading, and banking arrangement, such as is now being considered for heavy-duty truck engines. Beginning with some interim emissions control level which could be achieved without significant external changes to the engine, the required corporate average emissions levels could be reduced each year until they reached the ultimate control levels desired. In this way, stringent emission controls could be designed into new models as they are released.

Estimates of the achievable intermediate-term and long-term (advanced technology) corporate average emission control levels for agricultural engines are shown in Table 6-3. Two sets of standards are presented: one based on a steady-state test cycle, and the other on a test cycle including transient operation. The former would be applicable to combines, windrowers, large tractors, and other equipment operated primarily in steady-state conditions. The latter would apply to loaders, and possibly to small utility tractors. The major differences between these two test cycles are in the PM and HC standards achievable; achievable NO_x emissions are little affected by transient operating conditions.

TABLE 6-3. ESTIMATED ACHIEVABLE EMISSIONS CONTROL STANDARDS FOR DIESEL ENGINES USED IN FARM EQUIPMENT

	Emissions Limit (g/BHP-hr)	Equivalent Emission Factor (lb/1000 gal.)
STEADY-STATE TEST CYCLE		
Intermediate Control Level		
NOx	8.00	317
HC	0.50	20
PM	0.50	20
Advanced Technology		
NOx	6.00	238
HC	0.20	8
PM	0.15[1]	6
TRANSIENT TEST CYCLE		
Intermediate Control Level		
NOx	8.00	317
HC	1.00	40
PM	0.80	32
Advanced Technology		
NOx	6.00	238
HC	0.30	12
PM	0.15[1]	6

Source: Radian estimates.

[1] Due to high load factors, the ability of farm equipment to meet the 0.1 g/BHP-hr standard established for highway trucks is questionable. We have used a more conservative estimate.

As with the previous sections, the reader is warned that these are engineering estimates only, based on very limited data, and intended only to indicate the potential benefits of regulation in this area. Additional research to confirm these estimates would be essential before these or any other emission standards were incorporated into law.

Near-term emissions control technologies applicable to agricultural equipment include: retarded injection timing, increased injection pressures, improvements in air flow and combustion chamber geometry, and similar engine optimization measures. In addition, turbocharging would be feasible in many (but by no means all) equipment models which are currently using naturally-aspirated engines. Addition of low-temperature, separate circuit aftercooling would also be possible for some existing turbocharged or turbocharged/aftercooled engines, but again, not all of them. It should be noted that all of these steps would involve some economic waste, as the vehicle drivetrain would be unable, in most cases, to absorb the increased power output available with turbocharging and/or aftercooling. This would require that the engine be derated to match its previous power level.

Other near-term technologies applicable to agricultural engines include exhaust gas recirculation (EGR) and/or indirect injection in the small Group 4 engines used for utility tractors and compact loaders, and possibly in higher-powered, low usage engines such as those in combines. EGR is unlikely to see much application in large tractors, due to its adverse effects on engine wear and durability. Trap-oxidizers would also be applicable in applications such as combines, where the high and predictable engine load would eliminate regeneration problems.

Advanced emission control technologies, which could be designed into new equipment models as they are produced, include turbocharging with moderately low-temperature aftercooling in most engines, electronic injection timing and governor control, further optimization of combustion chamber, airflow, and injection characteristics, reduced oil consumption, and trap-oxidizers with precious-metal catalysts for HC control. These last would require the use of low-sulfur fuel, but EPA is presently considering mandating this in any event. Due to the relatively high load factors experienced, trap-oxidizer regeneration would be much less of a problem in agricultural applications than in on-highway trucks. For the same reason, however, formation of particulate sulfates by the catalyst would be more of a problem. These considerations are reflected in the estimates shown in Table 6-3.

Because of the limited space available for heat exchangers and the adverse operating conditions imposed by field work, air-to-air heat exchangers would be infeasible for most agricultural machines. These same conditions would limit the size and potential effectiveness of separate-circuit aftercoolers or other low-temperature aftercooling techniques. For these reasons, the degree of NO_x reduction achievable in farm equipment would be less than that which could be achieved in on-highway trucks or marine engines. This is reflected in the higher NO_x standards shown in Table 6-3.

6.6 Cost-Effectiveness Analysis

Table 6-4 shows some extremely rough calculations of the costs and cost-effectiveness of controlling emissions to the "intermediate" level shown in Table 6-3. Due to the uncertainty of costs and technology involved in reaching the "advanced technology" level, no meaningful cost-effectiveness estimates for that control level were possible.

Cost-effectiveness estimates are presented for three different types of agricultural equipment: a large four-wheel drive tractor, a small utility tractor, and a combine. Emission controls assumed for the large tractor include retarded timing, increased injection pressure, and a low-temperature aftercooler, plus combustion chamber optimization. This technology was assumed to be adapted from on-highway versions of the same engine. For the small tractor, retarded injection timing retardation, combustion chamber and airflow optimization, and moderate EGR were assumed. For the combine engine, we assumed the use of a commercially-available truck engine rating rather than the off-highway version of the engine, with a corresponding increase in cost.

TABLE 6-4. ESTIMATED COST-EFFECTIVENESS OF EMISSIONS CONTROL FOR DIESEL ENGINES USED IN FARM EQUIPMENT

	Large 4WD Tractor	Small Tractor	Combine
COST OF EMISSION CONTROLS			
Engine Horsepower	227	56	136
Initial Cost of Controls	$1,500	$300	$500
Engine Life (yrs)	15	15	15
Amortized Cost/year @ 10%	$197	$39	$66
Fuel Cons. Increase	2%	5%	5%
Annual Fuel Cons. (Gal)			
Baseline	4,300	220	700
With controls	4,386	231	735
Added Fuel Cost @ $0.80/gal	$69	$9	$28
Addl. Ann. Maintenance	$100	$30	$50
Annualized Control Cost Per Unit	$306	$58	$104
EMISSIONS			
Emission Factors (lb/1000 gal.)			
Baseline			
NOx	435	434	530
HC	35	75	86
PM	32	51	60
With Controls			
NOx	317	317	317
HC	20	40	20
PM	20	32	20
Annual Emissions (lbs per unit per year)			
Baseline			
NOx	1,871	95	371
HC	151	17	60
PM	138	11	42
With Controls			
NOx	1,390	73	233
HC	88	9	15
PM	88	7	15
Emissions Reduction (lbs per unit per year)			
NOx	480	22	138
HC	63	7	46
PM	50	4	27
Cost-Effectiveness ($/ton)			
NOx + HC	$845	$2,960	$848
PM	$3,067	$7,607	$1,900

7.0 CONSTRUCTION AND INDUSTRIAL EQUIPMENT

Construction equipment includes earthmoving and related machinery such as bulldozers, graders, scrapers, loaders, cranes, backhoes, and off-highway trucks. Industrial equipment such as front-end loaders and industrial tractors is also included in this category, as are specialized mining and logging machines such as log skidders.

7.1 Engine Characteristics and Operating Conditions

Diesel engines used in construction and industrial equipment (CIE) range from less than 40 HP for forklifts and small loaders to more than 800 HP for the largest earthmoving machines and off-highway trucks. Most CIE engines are relatively small, naturally-aspirated, moderate-speed engines classed in Groups 2 and 4. Many of these are generally specially designed for their applications, or adapted from engines used in small agricultural tractors. The larger engines used in large earthmoving and similar machinery are less numerous, but--due to their high power output and greater utilization--account for a significant fraction of the total emissions from this category. These engines are classed in Groups 2 and 3, and are often adapted from truck engine designs (or vice versa). Many of these larger engines use turbocharging and (sometimes) intercooling to increase their power output.

Usage patterns in construction and industrial equipment engines are as varied as the equipment types themselves. Hydraulic pumps to power the booms, lifts, buckets, blades, and other implements are a large part of the engine load in most types of construction and industrial equipment, and in some cases (e.g. hydrostatically driven crawlers) they are nearly the entire load. Some cranes and large earthmoving machines use diesel-electric systems like those in locomotives. In most construction equipment, however, a large part of the engine power requirement is for moving the machine, through a direct mechanical linkage with the wheels or tracks.

Hydrostatic and diesel-electric drive systems allow the engine to maintain a relatively constant speed, although the engine torque required at that speed may fluctuate. Direct mechanical drive, on the other hand, imposes large transient changes in speed and load on the engine. The need to generate full or near-full engine torque at low engine speeds in many operating cycles leads to high transient smoke, and probably high particulate emissions as well.

Diesel engines in construction machinery must operate in a brutal physical environment. This is especially true of engines in mechanical-drive applications, where shock and vibration loads may be transmitted through the drivetrain to the engine. Reliability is also very important--failure of a few large machines could seriously disrupt a construction schedule. This imposes stringent requirements for robustness and reliability on the engine. To be commercially feasible, any emission controls would have to be similarly robust and reliable.

7.2 Current Emission Factors

The best data on emission factors for construction and industrial equipment are contained in a report to the California Air Resources Board by Environmental Research and Technology (ERT) (1982). This report was sponsored by the farm equipment, construction equipment, and engine industries through their respective associations, and includes massive amounts of manufacturer-supplied data. Although the report deals specifically with California, the emission factor data contained in it are the best available for remainder of the U.S. as well. These data are presented in Table 7-1.

As discussed in Section 6-2, the data in the ERT report suffer from several limitations. The most important of these is the absence of particulate measurements. As a result, the PM emission factors in Table 7-1 were taken from AP-42 (EPA, 1985). EMA's criticism of these emission factors, and our response, have already been discussed in Section 6-2. As was also the case with farm equipment, we decided to retain these factors essentially for lack of

TABLE 7-1. ESTIMATED CURRENT EMISSION FACTORS FOR DIESEL ENGINES USED IN CONSTRUCTION AND INDUSTRIAL EQUIPMENT

	EMISSION FACTORS (G/BHP-HR)			
	HC[1]	CO[1]	NOx[1]	PM[2]
Equipment Type				
Track Type Tractor, 90+ HP	0.37	1.65	6.60	0.69
Track Type Tractor 20-89 HP	1.33	2.91	9.63	0.66
Track Type Loader, 90+ HP	0.47	1.56	7.76	0.66
Track Type Loader, 20-89 HP	1.80	3.02	10.97	0.69
Wheel Loader > 2-1/2 cubic yard	0.60	2.07	8.31	0.81
Wheel Loader < 2-1/2 cubic yard	1.29	3.26	9.24	0.81
Industrial Wheel Tractor	1.76	7.34	11.91	1.27
Skid-Steer Loader	1.76	7.34	11.91	1.27
Wheel Tractor Scraper	0.55	2.45	7.46	0.79
Off-Highway Truck*	0.37	2.28	8.15	0.50
Motor Grader	0.36	1.54	7.14	0.63
Hydraulic Excavator, All	1.22	3.18	11.01	0.90
Trencher	1.10	4.57	10.02	0.90
Concrete Paver**	1.10	4.57	10.02	0.90
Bituminous Paver	0.99	5.19	11.18	0.90
Roller Compactor, Vibratory	1.06	6.72	14.27	0.78
Roller Compactor, Static	0.88	5.33	11.84	0.78
Crane, Wheel	0.59	4.99	12.45	0.90
Crane, Crawler	0.59	4.99	12.45	0.90
Crane, Hyd., Wheel, 1-Station	0.80	7.80	14.69	0.90
Crane, Hyd., Wheel, Multi-Station	0.68	3.71	12.47	0.90
Log Skidder	0.61	3.18	9.82	0.90
Pipe Layer	0.59	4.99	12.45	0.90
Fuel-Weighted Emission Factors				
lb/1000 gal	29	117	360	31
g/BHP-hr	0.74	2.94	9.08	0.77

* Also wheel dozer, pavement cold planer.

**Also generators, pumps, compressors

Sources:

[1] ERT, 1982.

[2] EPA, AP-42, 1985.

any more applicable data. As the PM factors used for construction equipment are generally lower than those used in farm equipment (reflecting the more modern, larger, and cleaner engines tested), they may be considered less objectionable as a result. Research to obtain more recent and applicable emissions data for construction equipment is strongly recommended, however.

Also shown in Table 7-1 are a set of "fuel-weighted" emission factors for construction and industrial equipment. These are the weighted averages of the emission factors for each equipment type, with the weighting proportional to the fuel consumed by each type of machine. Fuel consumption estimates for each machine type are shown in Table 7-2.

A major limitation of both the ERT data and the AP-42 particulate factors is the fact that both were based on the old 13-mode steady-state test cycle, and thus do not account for any transient effects. Since most construction equipment operation involves a highly transient duty cycle, this is a much greater problem for construction and industrial equipment than for farm equipment. Many construction equipment operating cycles require full or near-full engine torque at low engine speeds--a situation which can produce very high particulate emissions. The frequent puffs of black smoke emitted by many construction machines operated on such cycles are testimony to the potential for high emissions. As a result, the HC and PM emissions factors shown in Table 7-1 may significantly understate the real emissions. Research to resolve this issue is recommended.

7.3 Engine Population and Emission Factor Data

Population and emission estimates for construction and industrial equipment are listed in Table 7-2. The utilization and duty-cycle data in this table were taken from the ERT report to the California Air Resources Board (1982). At the time our Task 1 interim report was prepared, no national-level population data were available for construction and industrial equipment. As a result, national populations were calculated by scaling up the California

TABLE 7-2. ESTIMATED POPULATION, FUEL CONSUMPTION AND EMISSIONS FROM DIESEL ENGINES USED ON CONSTRUCTION AND INDUSTRIAL EQUIPMENT

	Diesel[1] Population	Usage[3] (hr/yr)	Avg.[3] H.P.	Load[3] Factor	Consumption[4] (1000 gal)	EMISSIONS (TONS/YEAR) HC	CO	NOx	PM
Equipment Type									
Track Type Tractor, 90+ HP	84,000	1350	216	0.41	557,928	4,092	18,249	72,998	7,654
Track Type Tractor 20-89 HP	36,000	865	63	0.38	41,416	1,092	2,389	7,906	538
Track Type Loader, 90+ HP	36,000	1175	146	0.44	150,964	1,407	4,669	23,223	1,960
Track Type Loader, 20-89 HP	28,000	850	67	0.50	44,294	1,581	2,652	9,633	608
Wheel Loader > 2-1/2 cubic yard	74,000	1430	229	0.40	538,506	6,405	22,098	88,711	8,594
Wheel Loader < 2-1/2 cubic yard	56,000	1035	87	0.32	89,645	2,292	5,793	16,420	1,431
Industrial Wheel Tractor	212,000	556	56	0.38	139,548	4,869	20,305	32,947	3,513
Skid-Steer Loader	112,000	500	40	0.32	39,822	1,389	5,794	9,402	1,003
Wheel Tractor Scraper	16,400	750	289	0.42	82,943	904	4,028	12,266	1,297
Off-Highway Truck	20,000	2940	623	0.28	569,837	4,180	25,756	92,065	5,671
Motor Grader	74,000	1035	43	0.41	75,016	535	2,290	10,618	929
Hydraulic Excavator, All	63,000	1430	200	0.49	490,490	11,863	30,920	107,054	8,770
Trencher	50,500	572	75	0.49	58,976	1,286	5,343	11,715	1,055
Concrete Paver	11,300	500	185	0.38	22,066	481	1,999	4,383	395
Bituminous Paver	12,000	820	120	0.30	19,680	386	2,025	4,362	352
Roller Compactor, Vibratory	14,000	1085	140	0.25	29,536	621	3,935	8,355	456
Roller Compactor, Static	29,000	850	67	0.38	34,866	608	3,684	8,184	538
Crane, Wheel	38,000	760	90	0.40	57,760	676	5,714	14,256	1,033
Crane, Crawler	14,300	1085	150	0.25	32,324	378	3,198	7,978	578
Crane, Hyd., Wheel, 1-Station	34,700	1085	150	0.25	78,436	1,244	12,128	22,842	1,403
Crane, Hyd., Wheel, Multi-Station	6,100	760	90	0.40	9,272	125	682	2,292	166
Log Skidder	25,455[2]	1450	105	0.53	114,113	1,380	7,194	22,214	2,040
Pipe Layer	750[2]	1325	175	0.23	2,222	26	220	548	40
TOTAL	1,047,805				3,279,661	47,820	191,064	590,372	50,021
DOE/EIA "Off-Highway" Fuel Cons.					1,616,685[5]	23,572[6]	94,184[6]	291,019[6]	24,657[6]

Sources:

[1] *Construction Equipment* Magazine, March-July, 1987.
[2] Radian estimates based on California data.
[3] ERT, 1982.
[4] Calculated by assuming fuel consumption of 0.4 lb/BHP-hr.
[5] EIA, 1985.
[6] "Fuel-weighted" emission factors times DOE/EIA estimate.

populations estimated as a part of the ERT study. This was accomplished by dividing the California population by the ratio of 1979 California sales to 1979 U.S. sales of construction and industrial equipment.

In comments on our interim report, the Engine Manufacturer's Association accepted this general approach, but suggested that the estimated populations be adjusted downward to reflect declining sales of construction and industrial equipment since 1979 (Young, 1987). Since that time, however, Construction Equipment Magazine has published the result of a nationwide survey of construction equipment users, including population estimates for nearly all major classes of construction equipment (Landers, 1987). These population estimates, adapted to fit the classifications used in the ERT report, are the ones shown in Table 7-2. Although the equipment classes in this survey were not precisely coincident with those in the ERT report, the correspondence was close enough in every case to allow a reasonable allocation to be made.

Several categories shown in Table 7-2 require some additional explanation. The Construction Equipment survey estimated the number of backhoe loaders, which the ERT report lumped with other, similar machines as "industrial wheel tractors". The Construction Equipment estimate of 189,000 backhoe loaders was arbitrarily increased by 40 percent to reflect the presence of other classes of industrial tractors not included in the survey. This was then reduced by 20 percent to reflect the assumed fraction of gasoline engines in the population.

The ERT report included no equipment category for skid-steer loaders, although these are extremely common small construction machines. We assumed that the emission factors and usage patterns for these machines would be similar to those for industrial wheel tractors, and further assumed that 80 percent of the skid-steer loaders reported were diesel powered. These estimates are reflected in Table 7-2. In addition, the Construction Equipment survey contained no data for log skidders or pipelayers. Population estimates for these equipment types were carried over from our Task 1 interim report.

Total fuel consumption and pollutant emissions by construction and industrial equipment were calculated using the same approach as for farm equipment, and are also reported in Table 7-2. As this table indicates, no one category of construction and industrial equipment is dominant. The four largest categories are track-type tractors, large wheel loaders, hydraulic excavators, and off-highway trucks, but many other equipment categories are also major contributors.

Table 7-2 also shows the total fuel consumption calculated from the ERT data and, for comparison, the total fuel consumption for "off-highway" equipment estimated by DOE. As the table shows, the DOE estimate is only about half of the value calculated from our estimates. Whether this is due to an overestimate on our part (as a result of unrealistically high load factors, usage estimates, or average horsepower, for instance), or to an underestimate on DOE's part is unclear. As a matter of interest, the emissions which would result from assuming that the DOE value is correct, and scaling back the ERT estimates proportionally, are also shown.

7.4 Emissions Test Cycles

As discussed in Section 7.2 above, the operating cycles of many types of construction machinery include large transient changes in engine speed and load. A front-end loader, for instance, cycles between full engine power and low-load operation at least three times in the course of a loading cycle, which may take only 15-30 seconds to complete. Hydraulic excavators and other construction machines exhibit similar large cyclic swings in engine load and speed. These often result in high visible smoke emissions, and it is likely that they cause high PM emissions as well.

Due to the large number of machine designs and duty cycles, it would be impractical to develop an emissions test cycle reflecting each specific operating pattern. However, by recording speed and load measurements on a large number of engines in different types of construction machines, it might be possible to develop a "generic" transient test cycle which would result in adequate control of transient emissions effects over a wide range of cycles. An engine certified on this test cycle could then be used in any construction machine.

To allow for the fact that some construction machinery engines (those in paving machines, or compressors, for instance) do not experience large transient speed and load changes, the regulations might permit a manufacturer to certify an engine using a cycle of his own devising, as long as he could show that the cycle was representative of operation in a specific equipment model or models. The engine would then be limited to use in that type of equipment. This would avoid imposing technologies to control transient or low speed/high load emissions on engines which do not experience these operating conditions. It would also encourage manufacturers to develop equipment designs whose power requirements are more compatible with low emissions.

7.5 Feasibility of Emissions Control

Most construction and industrial equipment engines are classed in Group 2 or Group 4, with some high-powered earthmoving machinery being equipped with Group 3 engines. All three of these engine groups are closely related to on-highway engines, so that most emission control technologies developed for on-highway use should be readily adaptable. As with farm equipment, however, the differences in duty cycle, application requirements, and environmental conditions between the two types of applications will impose some limitations. In particular, the close integration of the engine and the machine as a whole, already discussed in relation to farm equipment, is an important consideration for construction and industrial equipment as well.

Like farm machinery, bulldozers, loaders, compactors, and similar machines are literally designed around the physical dimensions and operational capabilities of the engine, and any change in physical dimensions or torque capabilities may require redesign of major portions of the equipment. As with farm machinery, the economic life of an equipment design is of the order of ten years, after which the unit will be completely re-engineered and re-tooled. Thus, to avoid undue financial and engineering burden on the industry, it would be desirable to phase in any emission regulations stringent enough to require significant engine changes, using an approach such as the averaging, trading, and banking arrangement discussed in Section 6.5.

Estimates of the achievable intermediate-term and long-term (advanced technology) corporate average emission control levels for construction and industrial equipment engines are shown in Table 7-3. These estimates are identical to the estimates of achievable farm equipment emissions standards in Table 6-3. Two sets of standards are presented: one based on a steady-state test cycle, and the other on a test cycle including transient operation. The former would be applicable to pavers, compressor motors, and other engines operating in more-or-less steady-state conditions, while the latter would apply to the great majority of construction equipment types and models.

As in the previous sections, the reader is warned that these are engineering estimates only, based on very limited data, and intended only to indicate the potential benefits of regulation in this area. Additional research to confirm these estimates would be essential before these or any other emission standards were incorporated into law.

Near-term emissions control technologies applicable to construction and industrial equipment are identical to those for farm equipment. These include: retarded injection timing, increased injection pressures, improvements in air flow and combustion chamber geometry, and similar engine optimization measures. Turbocharging would also be feasible in some equipment models which are currently using naturally-aspirated engines, and low-temperature, separate-circuit aftercooling would be possible for in some models currently using turbocharged or turbocharged/aftercooled engines. As with farm equipment, these steps would involve some economic waste, as the vehicle drivetrain would be unable, in most cases, to absorb the increased power output available with turbocharging and/or aftercooling. Other near-term technologies applicable to construction and industrial equipment include exhaust gas recirculation (EGR) and/or indirect injection in the Group 4 engines.

Advanced emission control technologies, which could be designed into new equipment models as they are produced, include turbocharging with moderately low-temperature aftercooling, electronic injection timing and governor control, and further optimization of combustion chamber, airflow, and injection characteristics. Since many construction machines require high torque output at low RPM, variable-geometry turbochargers would also be well suited both for emissions control and for improving performance. Finally, trap-oxidizers with precious-metal catalysts would be well-suited for PM and HC control. Due to the relatively high load factors experienced, trap-oxidizer regeneration would be much less of a problem in construction equipment than in on-highway trucks, and trap-oxidizers have in fact been applied to some underground mining machines (Brev et al., 1987). The high load factors would produce a greater problem with particulate sulfate formation due to the catalyst, however, necessitating the use of low-sulfur fuel. These considerations are reflected in the estimates shown in Table 7-3.

As with farm equipment, the constraints of physical space and operating environment would rule out the use of air-to-air aftercoolers in most construction and industrial equipment, and would limit the applicability of other low-temperature aftercooling techniques. Thus, the NO_x reductions achievable would be less than those in on-highway truck engines. This is reflected in the higher NO_x standards shown in Table 7-3.

7.6 Cost-Effectiveness Analysis

Table 7-4 shows some extremely rough calculations of the costs and cost-effectiveness of controlling emissions to the "intermediate" level shown in Table 7-3. The uncertainties in the costs and technology involved in reaching the "advanced technology" level were such that no meaningful cost-effectiveness estimates for that control level were possible.

TABLE 7-3. ESTIMATED ACHIEVABLE EMISSIONS CONTROL STANDARDS FOR DIESEL ENGINES USED IN CONSTRUCTION AND INDUSTRIAL EQUIPMENT

	Emissions Limit (g/BHP-hr)	Equivalent Emission Factor (lb/1000 gal.)
STEADY-STATE TEST CYCLE		
Intermediate Control Level		
NOx	8.00	317
HC	0.50	20
PM	0.50	20
Advanced Technology		
NOx	6.00	238
HC	0.20	8
PM	0.15[1]	6
TRANSIENT TEST CYCLE		
Intermediate Control Level		
NOx	8.00	317
HC	1.00	40
PM	0.80	32
Advanced Technology		
NOx	6.00	238
HC	0.30	12
PM	0.15[1]	6

Source: Radian estimates.

[1] Due to high load factors, the ability of construction equipment to achieve the 0.10 g/BHP-hr standard established for highway trucks is questionable. We have used a more conservative estimate.

Cost-effectiveness estimates are presented for three different types of construction equipment: a hydraulic excavator, an industrial utility tractor, and a concrete paver. The excavator and tractor represent transient operation at high and low power levels, respectively, while the concrete paver is representative of steady-state operation. Except for the transient operating cycle experienced by the hydraulic excavator, these machines exhibit very similar power levels and operating characteristics to the three agricultural equipment types analyzed in Table 6-4.

Emission controls assumed for the hydraulic excavator included retarded timing, increased injection pressure, and a separate-circuit or air-air aftercooler, plus combustion chamber optimization. This technology was assumed to be adaptable from similar on-highway engines. For the small tractor, retarded injection timing, combustion chamber and airflow optimization, and moderate EGR were assumed. These control techniques (and indeed, the tractor itself) are identical to those assumed for the small agricultural tractor in Table 6-4. For the concrete paver engine, as with the combine, we assumed the use of a commercially-available truck engine rating rather than the off-highway version of the engine.

The cost-effectiveness of emissions control for construction equipment was calculated in the same way as for farm equipment. We allocated 75 percent of the control cost, more or less arbitrarily, to reducing NO_x and HC emissions, and the remaining 25 percent to PM. The resulting cost-effectiveness values of $750 to $2,050 per ton of NO_x plus HC, and $4,000 to $9,000 per ton for PM are also in the low-to-middle portion of the cost range for other emissions control strategies, and are comparable to those for farm equipment. Unlike emission reductions from farm equipment, however, these reductions would occur primarily in urban areas. These cost-effectiveness estimates are thus directly comparable to those of other urban-oriented control strategies.

TABLE 7-4. ESTIMATED COST-EFFECTIVENESS OF EMISSIONS CONTROL FOR DIESEL ENGINES USED IN CONSTRUCTION EQUIPMENT

	Hydraulic Excavator	Indust. Wheel Tractor	Concrete Paver
COST OF EMISSION CONTROLS			
Engine Horsepower	200	56	185
Initial Cost of Controls	$1,200	$300	$600
Engine Life (yrs)	10	10	10
Amortized Cost/year @ 10%	$195	$49	$98
Fuel Cons. Increase	2%	5%	5%
Annual Fuel Cons. (Gal)			
Baseline	7,800	660	2,000
With controls	7,956	693	2,100
Added Fuel Cost @ $0.80/gal	$125	$26	$80
Addl. Ann. Maintenance	$150	$40	$60
Annualized Control Cost Per Unit	$470	$115	$238
EMISSIONS			
Emission Factors (lb/1000 gal.)			
Baseline			
NOx	437	472	397
HC	48	70	44
PM	36	50	36
With Controls			
NOx	317	317	317
HC	40	40	20
PM	32	32	20
Annual Emissions (lbs per unit per year)			
Baseline			
NOx	3,409	312	794
HC	374	46	88
PM	281	33	72
With Controls			
NOx	2,522	220	666
HC	318	28	42
PM	255	22	42
Emissions Reduction (lbs per unit per year)			
NOx	887	92	128
HC	56	18	46
PM	26	11	30
Cost-Effectiveness ($/ton)			
NOx + HC	$748	$1,567	$2,045
PM	$8,969	$5,323	$3,961

It is worth noting that the cost per ton of particulate emissions eliminated in Table 7-4 may be greatly overestimated for the excavator and industrial tractor, due to the possible substantial under-estimate of the emissions reduction. This is due to the fact that the baseline emissions were calculated from the steady-state PM emission factors developed by Hare et al., (1975), while the "controlled" emission level is based on engine capabilities under transient conditions. Since uncontrolled transient emissions are often much higher than those in steady state, the emissions benefits of the intermediate-level standards may have been significantly underestimated.

8.0 MOBILE REFRIGERATION UNITS

Small, engine-powered refrigeration units are used to provide cooling for refrigerated trailers, shipping containers, truck bodies, and rail cars. These units are overwhelmingly diesel powered, due to the high efficiency of the diesel engine and the ready availability of its fuel. Although they are individually small in power output, the large number of refrigeration units in use and the large number of operating hours per unit make them a not-inconsiderable contributor to total diesel emissions.

Mobile refrigeration units have received relatively little study, compared to the other equipment categories considered in this report, and the funds available for this preliminary study did not permit an in-depth investigation. As a result, the estimates presented here are even more uncertain than those in the previous sections. More extensive investigation, including actual emissions testing of a sample of refrigeration units, is strongly recommended.

8.1 Engine Characteristics and Operating Conditions

Diesel engines used for mobile refrigeration are typically small, naturally-aspirated, high-speed engines classed in Group 4. Power ratings range from less than 10 H.P. up to around 70 HP for some truck units, while railcar refrigeration units are reported to have an average of 88 H.P. Both direct-injected (DI) and indirect-injected (IDI) engines are used, but the market trend is toward increased use of DI engines. This is due to the greater fuel efficiency, lower heat losses, and easier cold starting of the DI engines.

Diesel engines in mobile refrigeration units typically run continuously while the unit is in use, being shut off only when the car or trailer will not be used for an extended period. In most units, the engine and compressor are sized to deal with the maximum anticipated cooling load. This may include cooling down a just-loaded cargo, as well as keeping it cool under the most extreme climatic conditions expected. As a result, they are substantially oversized for normal cooling requirements. Most mobile refrigeration units handle this by cycling between full-power operation with the compressor running and letting the engine idle when the compressor is not needed. Thus, depending on the cooling requirements of the load, the engine often spends the great bulk its time idling.

To reduce fuel consumption, some newer mobile refrigeration units are incorporating a more complex control strategy--for instance, using full-speed operation for rapid cooldown when required, and a slower, more fuel-efficient speed for keep-cool operation. Systems allowing automatic shutdown and restart of the engine when it is needed are also available. We were unable to determine the degree of market penetration of these systems, but it is believed to be relatively small.

8.2 Current Emission Factors

Emissions data for engines used in mobile refrigeration are unavailable. Table 8-1 shows some rough estimates of these factors, based on data for similar engines in other applications. For railcar refrigeration units, the most common engine is the DDA 2-71. The emission factors shown are based on a 6V-71 engine (Hare et al., 1975). This engine has more cylinders, but is otherwise similar to the 2-71 in combustion technology. The NO_x emissions for this engine reported by Hare, et al. have been adjusted downward somewhat, and the PM emissions adjusted upward to reflect the effects of wear in the injector linkage and changes in engine technology since 1975.

Even less information is available on emissions from engines in truck and container refrigeration units. The emission factors shown in Table 8-1 for these units are Radian estimates, based on typical emissions performance for small DI and IDI diesel engines, and may well be grossly wrong. It is likely that these emissions values vary greatly from manufacturer to manufacturer, so even a few emissions data points would not help greatly to improve the estimates.

TABLE 8-1. ESTIMATED CURRENT EMISSION FACTORS FOR DIESEL ENGINES USED FOR MOBILE REFRIGERATION

	EMISSION FACTORS	
	g/BHP-hr	lb/1000 gal.
Railroad Car Units[1]		
HC	1.0	40
CO	4.0	159
NOx	16.0	634
PM	0.4	16
Truck/Container Units[2]		
HC	1.2	48
CO	5.0	198
NOx	8.0	317
PM	0.6	24

Sources:

[1] Radian estimates based on DDA 2-71 engine.

[2] Radian estimates based on typical small DI and IDI engines.

8.3 Engine Population and Emissions Inventory

Estimated nationwide population, fuel consumption, and emissions for diesel engines used in mobile refrigeration units are shown in Table 8-2. Estimates of the national population of truck and container refrigeration units were obtained by summing annual sales data (obtained from Refrigerated Transporter magazine) over an estimated 15 year useful life. The number of refrigerated train units was taken from statistics of the Association of American Railroads (1986). The average horsepower, load factors, and hours-of-operation shown for these units are Radian estimates, based on limited data and conversations with persons involved in the industry.

Like the industries which use them, mobile refrigeration units should tend to be concentrated in urban areas and their immediate surroundings, as these are the major termini for refrigerated railcars and truck trailers. The degree of urban operation for these units is probably similar to that of the vehicles which transport them: trains and on-highway trucks.

8.4 Emissions Test Cycle

Emissions from a mobile refrigeration unit are affected by the overall design of the unit, including the compressor, heat-exchangers, and control system as well as the engine. An appropriate test procedure should therefore measure emissions against the useful output of the system: i.e. BTU of cooling supplied under specified conditions (which should include cyclic operation). This would result in emissions credit for shutdown/restart rather than continuous idle, use of more efficient compressors, and other design features which would reduce emissions in the real world. Unfortunately, sufficient data to specify such a test cycle were unavailable for this preliminary study. Thus, the discussion of achievable emissions standards in Section 8.5 is limited to g/BHP-hr numbers only.

TABLE 8-2. ESTIMATED NATIONWIDE POPULATION, FUEL CONSUMPTION, AND EMISSIONS FROM DIESEL ENGINES USED FOR MOBILE REFRIGERATION

Application	Est. Pop.	Avg.[3] HP	Usage[3] (hr/yr)	Load[3] Factor	Fuel Cons.[4] (1000 Gal)	Total Emissions (Tons/Yr)			
						HC	CO	NOx	PM
Train	30,000[1]	88	8000	0.2	234,667	4,693	18,656	74,389	1,877
Truck/Container	173,000[2]	27	5000	0.2	259,500	6,228	25,691	41,131	3,114
TOTAL	203,000				494,167	10,921	44,347	115,520	4,991

Sources:

[1] Association of American Railroads, 1986.

[2] Calculated from annual sales data, assuming 15-year life.

[3] Radian estimate.

[4] Calculated assuming fuel consumption of 0.4 lb/BHP-hr.

8.5 Feasibility of Emissions Control

Emission control techniques applicable to mobile refrigeration engines in the intermediate term include indirect injection or optimized direct-injection combustion systems, retarded injection timing, combustion chamber optimization, and exhaust gas recirculation. The emissions standards estimated to be achievable through these techniques are shown in Table 8-3. These standards are based on the 1988 on-highway truck standards (adjusted to reflect steady-state operation), and are probably somewhat conservative. Many existing IDI engines can undershoot these standards by a considerable margin. Wade and co-workers (1985) have also demonstrated the capability to control small DI engine emissions to levels well below the values shown. As before, however, the reader is cautioned that these estimates are preliminary only, and that additional research to confirm these estimates would be needed before these or any other emission standards were incorporated into law.

The major advanced emission control technologies applicable to mobile refrigeration engines would be catalytic trap-oxidizers, in combination with EGR and an electronic engine control system. The figures for "advanced technology" in Table 8-3 reflect these technologies. The major problem facing trap-oxidizer development in motor vehicles is the unpredictability of the operating conditions, which complicates regeneration system design. Since the engine in a mobile refrigeration unit is under complete independent control, the regeneration system could be simple. Successful trap-oxidizer operation in a similar application (a diesel-powered heat-pump) was demonstrated some years ago by Volkswagen.

8.6 Cost-Effectiveness Analysis

Table 8-4 shows some very rough estimates of the cost-effectiveness of the "intermediate" emissions control levels in mobile refrigeration units for railcar and truck/container service. The control costs shown assume the application of engine modifications, retarded timing, and either EGR or

TABLE 8-3. ESTIMATED ACHIEVABLE EMISSIONS CONTROL STANDARDS FOR DIESEL ENGINES USED IN MOBILE REFRIGERATION

	Emissions Limit (g/BHP-hr)	Equivalent Emission Factor (lb/1000 gal.)
Intermediate Control Level		
NOx	6.00	238
HC	1.00	40
PM	0.50	20
Advanced Technology		
NOx	5.00	198
HC	0.30	12
PM	0.10	4

Source: Radian estimates.

TABLE 8-4. ESTIMATED COST-EFFECTIVENESS OF EMISSIONS CONTROL FOR DIESEL ENGINES USED IN MOBILE REFRIGERATION

	Train car	Truck and Container
COST OF EMISSION CONTROLS		
Engine Horsepower	88	27
Initial Cost of Controls	$600	$400
Engine Life (yrs)	15	15
Amortized Cost/year @ 10%	$ 79	$ 53
Fuel Cons. Increase	3%	2%
Annual Fuel Cons. (Gal)		
Baseline	7,800	1,500
With controls	8,034	1,530
Added Fuel Cost @ $0.80/gal	$187	$ 24
Addl. Ann. Maintenance	$ 80	$ 40
Annualized Control Cost Per Unit	$346	$117
EMISSIONS		
Emission Factors (lb/1000 gal.)		
Baseline		
NOx	634	317
HC	40	48
PM	16	24
With Controls		
NOx	238	238
HC	40	40
PM	20	20
Annual Emissions (lbs per unit per year)		
Baseline		
NOx	4,945	476
HC	312	72
PM	125	36
With Controls		
NOx	1,912	364
HC	321	61
PM	161	31
Emissions Reduction (lbs per unit per year)		
NOx	3,033	111
HC	(9)	11
PM	(36)	5
Cost-Effectiveness ($/ton)		
NOx + HC	$229	$1,909

turbocharging and aftercooling for emission control purposes. These cost estimates are highly uncertain--much more investigation of the technology and operating constraints would be required to develop reliable cost estimates for these engines.

A similar level of uncertainty surrounds the emission reduction estimates. Due to the absence of data on current emissions, the emission reductions available are uncertain, as is the cost-effectiveness of control. As Table 8-4 indicates, however, emissions control for these engines could potentially be highly cost-effective, with a cost per ton of HC and NO_x removed ranging from $229 to $1,909. This broad range suggests the level of uncertainty in the data. Further research to arrive at a more precise quantification of this potential is recommended.

9.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This section pulls together and summarizes the results detailed in the preceding five sections, and presents our conclusions and recommendations.

9.1 Summary and Conclusions

As the preceding five sections have shown, total pollutant emissions from off-highway diesel engines are large both in absolute terms and in proportion to their total numbers, power output, and fuel consumption. Table 9-1 summarizes the estimated population, annual fuel consumption, and emissions for the five classes of off-highway diesel engines considered in this report. Off-highway diesel engines are estimated to produce about 2.75 million tons of NO_x per year, 187,000 tons of particulate matter, 232,000 tons of unburned HC, and 959,000 tons of CO. These values are about 12.6 percent, 2.4 percent, one percent, and 1.25 percent, respectively, of estimated total emissions of these pollutants from all sources nationwide (EPA, 1986).

More significant than the off-highway diesel contribution to the total emissions inventory is the off-highway contribution to the total for all mobile diesel engines, both on and off-highway. Table 9-2 shows this calculation. As this table indicates, off-highway diesel engines are responsible for a disproportionate fraction of the total: accounting for 56 percent of the NO_x emissions, 57 percent of CO emissions, and 48 percent of HC emissions from mobile diesel engines, but only 41 percent of the diesel fuel burned. Their contribution to PM emissions is less than proportionate, however, at 36.5 percent of the total. Due to limited data, the numbers in Table 9-2 are somewhat crude, but the conclusion is inescapable: off-highway diesel engines are currently an important source of emissions, comparable in magnitude to on-highway diesels.

Diesel engines in on-highway vehicles have been subject to emission regulations for many years, and have recently received a great deal of

TABLE 9-1. ESTIMATED NATIONWIDE POPULATION AND EMISSIONS FROM DIESEL ENGINES USED IN OFF-HIGHWAY APPLICATIONS

	No. of Engines	Total Horsepower (1,000s)	Fuel Consumption (1,000 gal)	Emissions (tons/yr)			
				HC	CO	NO_x	PM
Locomotives							
Medium Speed	26,105	61,111	3,409,476	30,999	308,558	901,645	37,041
Percent of Nationwide[1]				0.13%	0.40%	4.16%	0.48%
Marine Vessels							
High Speed	438,000	45,471	915,671	14,651	54,482	199,616	10,988
Medium Speed	5,000	11,173	917,607	18,811	85,796	244,542	9,176
Total	443,000	56,644	1,833,278	33,462	140,278	444,158	20,164
Percent of Nationwide				0.14%	0.18%	2.05%	0.26%
Farm Equipment							
High Speed	3,868,019	332,139	3,021,561	108,603	274,669	688,874	75,103
Percent of Nationwide				0.46%	0.36%	3.17%	0.97%
Construction and Industrial Equipment							
High Speed	1,047,805	124,056	3,279,661	47,820	191,064	590,372	50,021
Percent of Nationwide				0.20%	0.25%	2.72%	0.65%
Mobile Refrigeration							
High Speed	203,000	9,518	494,167	10,921	44,347	115,520	4,991
Percent of Nationwide				0.05%	0.06%	0.53%	0.06%
TOTALS							
High Speed	5,556,824	511,184	7,711,060	181,995	564,562	1,594,382	141,103
Medium Speed	31,105	72,284	4,327,083	49,810	394,354	1,146,187	46,217
Total	5,587,929	583,468	12,038,143	231,805	958,916	2,740,569	187,320
Percent of Nationwide				0.98%	1.25%	12.63%	2.43%

[1] Percent of nationwide emissions inventory for that pollutant based on EPA (1986).

TABLE 9-2. COMPARISON OF NATIONWIDE FUEL CONSUMPTION AND EMISSIONS OFF-HIGHWAY VS. ON-HIGHWAY DIESELS

	Fuel Consumption (1,000 gal)	Emissions (tons/yr)			
		HC	CO	NO_x	PM
Off-Highway Diesels (mid-1980s)[1]					
Locomotives	3,409,476	30,999	308,558	901,645	37,041
Marine Vessels	1,833,278	33,462	140,278	444,158	20,164
Farm Equipment	3,021,561	108,603	274,669	688,874	75,103
Const./Ind. Equipt.	3,279,661	47,820	191,064	590,372	50,021
Mobile Refrigeration	494,167	10,921	44,347	115,520	4,991
Total Off-Highway	12,038,143	231,805	958,916	2,740,569	187,320
On-Highway-Diesels (calendar 1984)[2]					
Heavy-Duty Vehicles	NA	242,290	693,832	2,136,563	297,357
Light-Duty Vehicles	NA	8,820	28,634	44,052	28,634
Total On-Highway	17,279,650	251,110	722,466	2,180,615	325,991
Total: All Mobile Diesel Engines	29,317,793	482,915	1,681,382	4,921,184	513,311
Off-Highway as Percent of All Mobile Diesels	41.1%	48.0%	57.0%	55.7%	36.5%

[1] Source: Radian estimates.

[2] Source: EPA (1986).

regulatory attention, which will lead to still lower emissions in the future. Off-highway engines, since they do not fall under EPA's statutory authority, have not been regulated. For this reason, pollutant emissions per unit of work produced or fuel consumed by an average off-highway diesel are much higher than those for an on-highway engine, and the potential for future reductions in emissions is correspondingly greater.

As discussed in Sections Three through Eight, emission control technology for on-highway diesel engines is well developed, and this technology could be transferred to most off-highway engines as well. Off-highway diesel engines can be divided into high-speed and medium-speed classes, having rated operating speeds above or below 1300 RPM, respectively. Except for railway locomotives, the great majority of off-highway diesel engines are high-speed types. These share many design features with on-highway truck and light-duty vehicle engines, so that most emissions control technologies demonstrated in on-highway engines would be readily transferable. Medium-speed engines are used in railway locomotives and some marine vessels. Emissions control technology for these engines is less developed, but even the little work that has been done shows the potential for major reductions in emissions.

Sections Four through Eight include a case-by-case discussion of applicable emission control technologies and achievable emissions standards for diesel engines used in each class of off-highway equipment. Table 9-3 summarizes the emissions standards estimated to be achievable by each class, as well as the percentage reduction from present levels represented by these standards. In the intermediate term, engines in all classes except farm equipment and construction equipment were estimated to be capable of meeting emissions standards comparable to the California 1988 NO_x and PM standards for off-highway vehicles. Construction and farm equipment were estimated to require a higher NO_x limit, due to the limited potential for turbocharging and aftercooling.

Given time to develop advanced emission control technology, it was estimated that engines in railway locomotives and marine vessels would be able to comply with emissions standards comparable to the Federal 1991 standards for

TABLE 9-3. EMISSIONS STANDARDS ESTIMATED TO BE ACHIEVABLE BY EACH CLASS OF OFF-HIGHWAY DIESELS

	Intermediate		Advanced Technology	
	Standard (g/BHP-hr)	Percent Reduction	Standard (g/BHP-hr)	Percent Reduction
Locomotives				
NO_x	6.0	55%	5.0	63%
HC	0.50	52%	0.30	71%
PM	0.50	1%	0.20	60%
Marine Vessels				
Medium-Speed Engines				
NO_x	6.0	55%	5.0	63%
HC	0.50	52%	0.30	71%
PM	0.50	1%	0.20	60%
High-Speed Engines				
NO_x	6.0	45%	5.0	55%
HC	0.50	38%	0.50	38%
PM	0.50	17%	0.25	59%
Farm Equipment				
NO_x	8.0	30%	6.0	48%
HC	0.50	72%	0.20	89%
PM	0.50	60%	0.15	88%
Construction Equipment				
NO_x	8.0	12%	6.0	34%
HC	0.50	32%	0.20	73%
PM	0.50	36%	0.15	81%
Mobile Refrigeration				
NO_x	6.0	49%	5.0	58%
HC	1.0	10%	0.20	73%
PM	0.50	2%	0.10	80%

Source: Radian estimates.

on-highway vehicles, while those in mobile refrigeration units should be able to comply with standards comparable to the 1994 on-highway limits. Construction and farm equipment could meet PM standards similar to the 1994 levels, but--due to their higher load factors--might not be able to achieve the level of 0.10 g/BHP-hr mandated for on-highway engines. As is also true of on-highway engines, a reduction in diesel fuel sulfur content might be required to achieve these low particulate levels. In addition, construction and farm equipment would also require a slightly higher NO_x limit than that mandated for on-highway engines, due to the limited potential for low-temperature charge cooling.

The reader is warned that the emissions limits shown in Table 9-3 are engineering estimates only, based on very limited data, and intended only to indicate the potential benefits of regulation in this area. As discussed below, additional research to confirm these estimates would be essential before these or any other emission standards were incorporated into law.

Figures 9-1 through 9-3 show the potential effects of introducing the emissions standards listed in Table 9-3 on NO_x, HC, and PM emissions from each class of off-highway engines. The leftmost bar for each class represents the current situation, with no emissions control. The middle bar represents the emissions that would be experienced if all existing engines met the "intermediate" emissions standards, and the rightmost bar the emissions that would result if all existing engines met the "advanced technology" standards. The net reduction if every off-highway engine in use met the "advanced technology" standards would be about 1.4 million tons of NO_x, 162,000 tons of HC, and 146,000 tons of PM per year, or 52 percent, 70 percent, and 78 percent, respectively, of the current emissions of these pollutants. In reality, of course this would take a very long time to achieve, due to the need to turn over the existing engine population.

The cost-effectiveness of controlling off-highway diesel emissions to at least the intermediate-term standards shown is estimated to be very favorable compared to the costs of other available emission control measures of

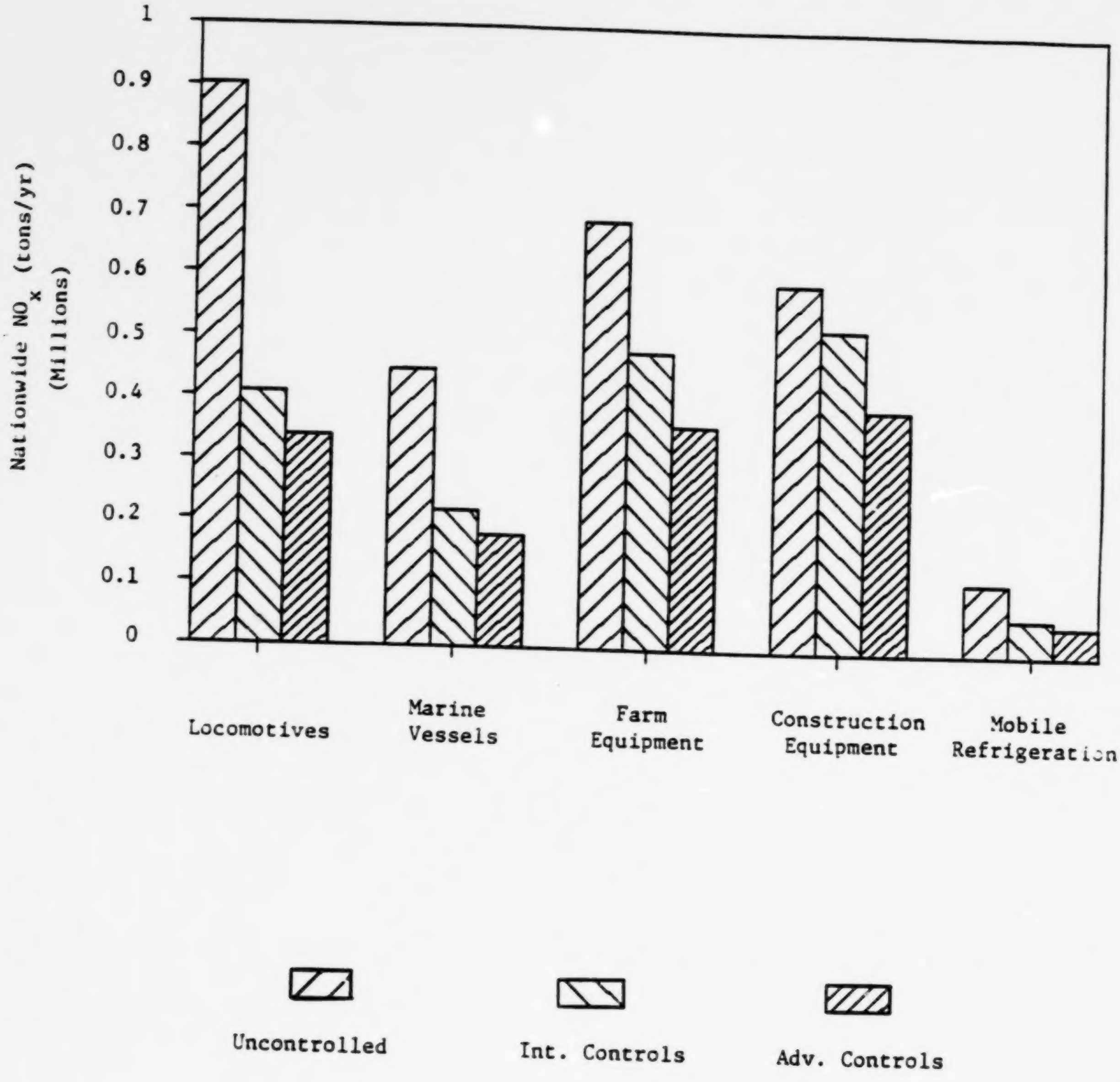

Figure 9-1. Estimated Effect of Emissions Controls on Total Off-Highway NO_x Emissions

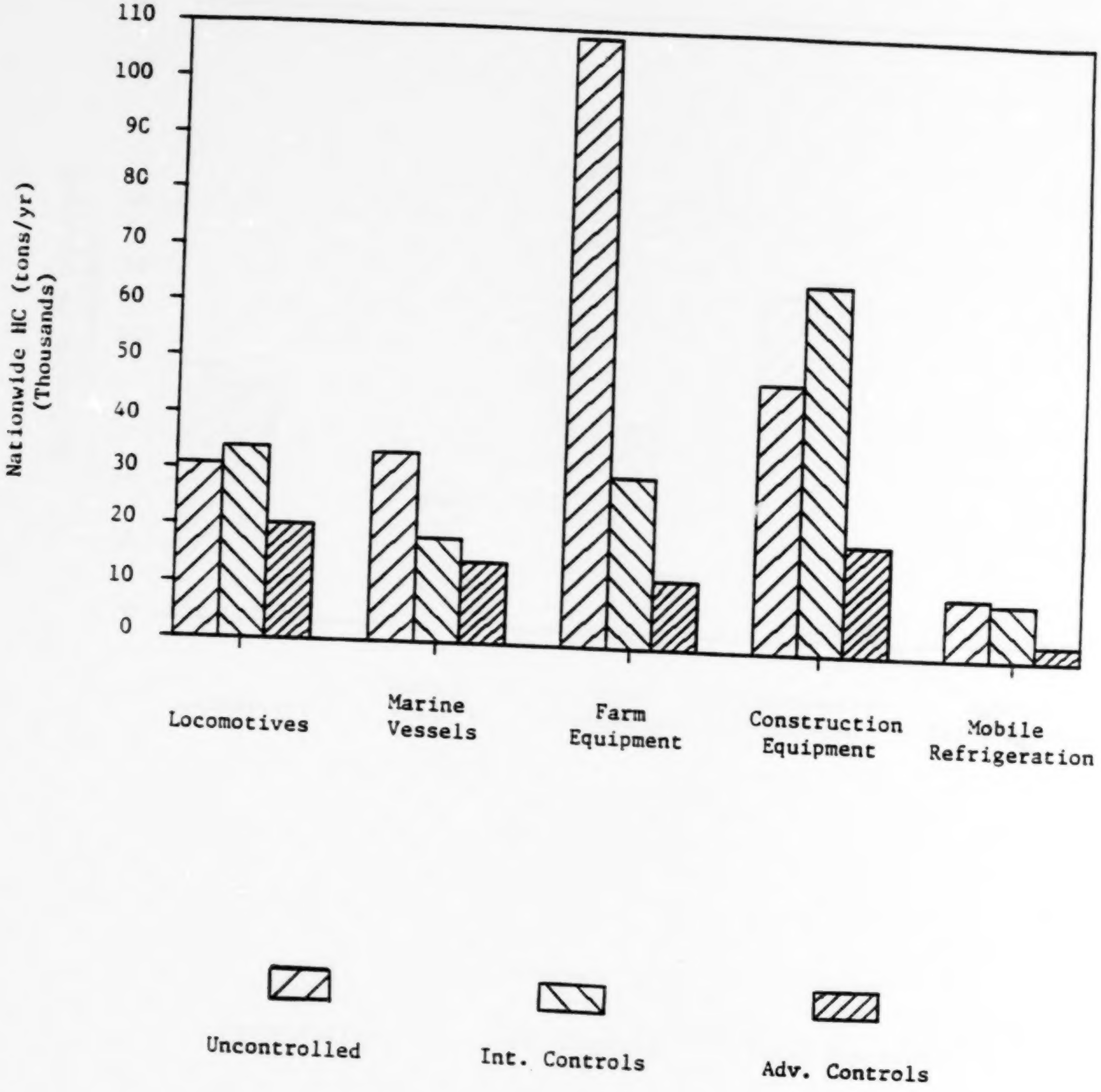

Figure 9-2. Estimated Effect of Emissions Controls on Total Off-Highway HC Emissions

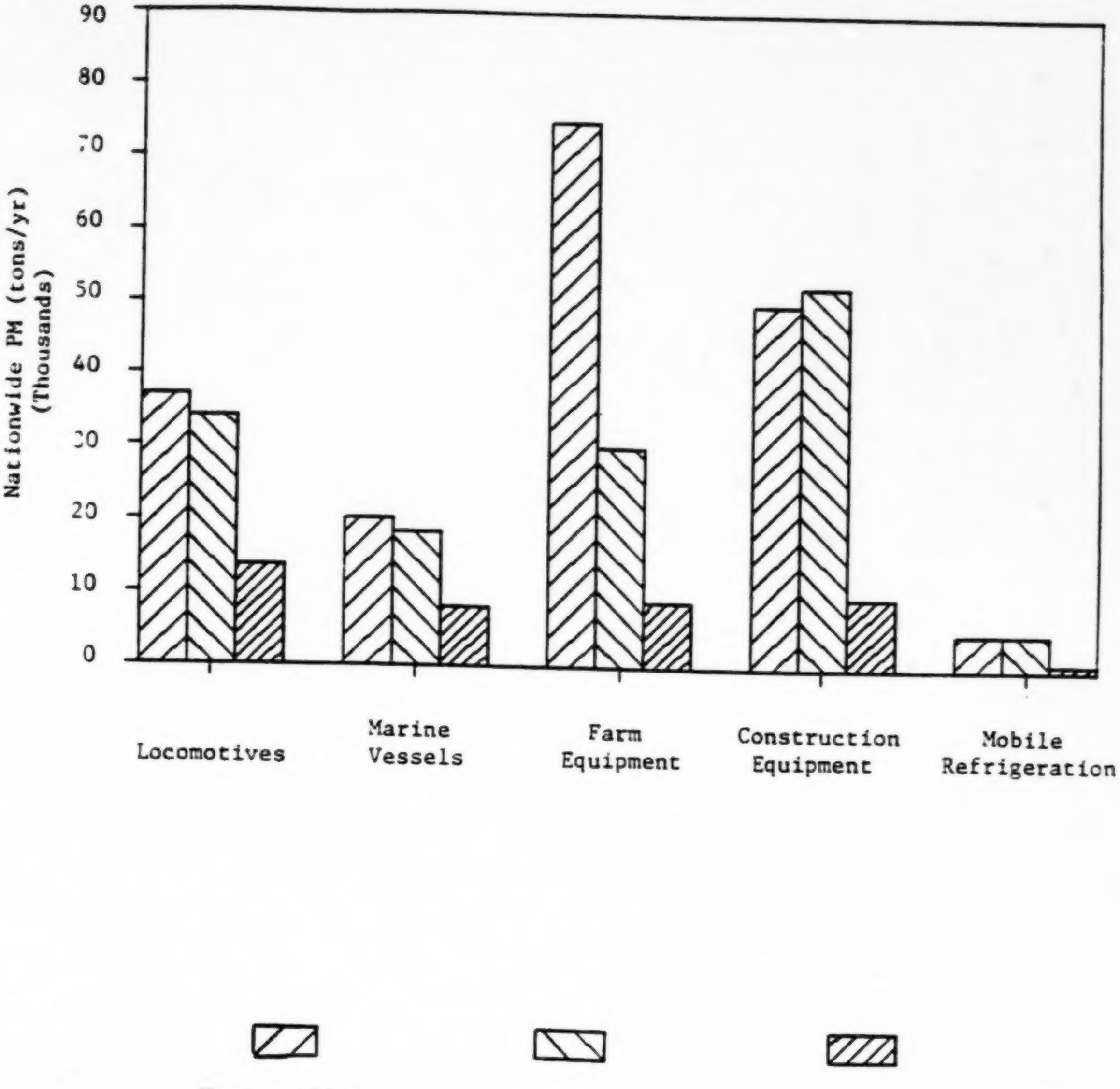

Figure 9-3. Estimated Effect of Emissions Controls on Total Off-Highway PM Emissions

similar significance. Estimated cost-effectiveness values for a number of specific equipment types are shown in Table 9-4. While based on crude preliminary cost estimates, these values are believed to somewhat conservative (in the sense of over-stating emissions control costs, and thus the costs per ton of pollutants eliminated). Despite this, the cost estimates for control of NO_x and HC range from a few hundred to about three thousand dollars per ton.

For comparison, the fuel cost alone for reducing the 1991 NO_x standard for heavy-duty on-highway engines from 5.0 to 4.0 g/BHP-hr (a step which is often suggested) is estimated at about $2,000 per ton (assuming a 4 percent fuel economy penalty and fuel at $0.80 per gallon excluding taxes). The incremental cost-effectiveness of the 1994 PM standard of 0.1 g/BHP-hr for heavy-duty on-highway engines has been estimated at about seven to eleven thousand dollars per ton (Weaver and Klausmeier, 1987a).

9.2 Recommendations

- Much research remains to be done to develop a more complete understanding of off-highway vehicle emissions, control technology, and cost. The following are some key areas for further research.

    1. Improved duty cycle characterization for all off-highway engine classes, leading to improved emissions measurements and to the development of representative test procedures.

    2. Development of suitable emissions measurement techniques for off-highway vehicles (such as marine vessels and construction equipment) for which dynamometric techniques are impractical. This will probably require portable sampling equipment to measure diesel emissions during normal operation of the vehicle.

    3. Extensive emissions measurements on current production engines, and on in-use equipment, leading to more accurate emission factors.

TABLE 9-4. ESTIMATED COST-EFFECTIVENESS OF "INTERMEDIATE LEVEL" EMISSIONS CONTROLS FOR DIFFERENT CLASSES OF OFF-HIGHWAY VEHICLES

	Cost Effectiveness (\$/ton)[1]	
	NO_x + HC	PM
Locomotives		
New	\$1,073	--[2]
Retrofit	1,332	--[2]
Marine Vessels		
Medium Speed	672	--[2]
High-Speed Propulsion	888	--[2]
High-Speed Generator	616	--[2]
Farm Equipment		
Large 4WD Tractor	845	3,067
Small Tractor	2,960	7,607
Combine	848	1,900
Construction Equipment		
Hydraulic Excavator	748	8,969
Industrial Tractor	1,567	5,323
Concrete Paver	2,045	3,961
Mobile Refrigerator		
Railcar Unit	229	--[2]
Truck/Container Unit	1,909	--[2]

[1] Approximate estimates based on engineering judgement and limited data. See text Chapters 4-8 for assumptions and limitations.

[2] PM reductions at "intermediate" control level are estimated as small or negative for these categories. This is due to low PM emissions to begin with, and the effects of the NO_x/PM tradeoff.

4. Development of improved estimates of engine populations, age and technology, utilization, and fuel consumption in order to provide accurate emissions inventories.

5. Assessment of urban-area and regional-scale effects of off-highway vehicle emissions.

6. Study of effects of available emission control technologies in individual engines and vehicles. It is recommended that EPA perform only preliminary studies in tis area, as experience has shown that detailed development and optimization of emissions controls is best left to the manufacturers.

7. Much more detailed analysis of the costs of control, including costs of accommodating any changes in engine performance and/or transient response.

8. Evaluation of in-use deterioration in emissions in off-highway equipment, including the effects of tampering and malmaintenance of emissions controls. A recent study for the California ARB (Weaver and Klausmeier, 1987b) concluded that these effects could result in heavy-duty truck PM emissions more than double the applicable standards, and similar increases might be expected in off-highway engines.

- In the event that emissions regulations are considered for farm and construction equipment engines, careful consideration should be given to phase-in mechanisms in order to avoid undue burden on the industry. An averaging, trading, and banking approach with "crawling" target levels, such as that discussed in Section 6.5, would be one fairly straightforward way to do this.

- In the event that emissions regulations are considered for new medium-speed marine and locomotive engines, consideration should also be given to establishing retrofit requirements for older engines in these categories. These requirements could most conveniently apply at the time of rebuild.

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APPENDIX A

TABLE A-1. SUMMARY OF EMISSION RATES FOR LOCOMOTIVE ENGINES IN SWRI TESTS

Engine	Hours	Notch	PARTICULATE		NOx		HC		CO	
			g/bhp-hr	lb/1,000 gal	g/bph-hr	g/lb fuel	b/bph-hr	g/lb fuel	g/bph-hr	g/lb fuel
GE	0	1	1.83	86.98	19.47	37.40	2.79	5.35	5.26	10.10
	0	2	1.11	41.67	18.83	44.13	1.89	4.41	2.26	5.30
	0	2	1.12	41.86	19.42	45.52	1.99	4.66	2.29	5.36
	0	3	0.88	34.93	16.57	41.01	1.81	4.49	2.08	5.15
	0	3	0.79	31.16	16.28	40.29	1.85	4.59	2.13	5.28
	0	4	0.51	20.84	14.94	37.90	1.80	4.56	3.09	7.84
	0	4	0.55	22.21	14.80	37.56	1.87	4.74	3.12	7.90
	0	5	0.55	23.27	13.72	36.39	1.73	4.59	4.25	11.26
	0	5	0.48	20.52	13.47	35.72	1.73	4.59	4.36	11.57
	0	6	0.51	22.16	11.69	32.92	1.50	4.10	6.07	16.57
	0	6	0.58	22.54	11.83	32.32	1.51	4.13	6.07	16.57
	0	7	----	-----	10.53	29.29	1.33	3.70	3.87	10.76
	0	7	0.46	20.34	10.54	29.30	1.33	3.70	3.78	10.51
	0	8	0.41	18.27	8.61	24.18	1.33	3.73	2.94	8.24
	0	8	0.42	19.06	8.38	23.52	1.31	3.68	2.94	8.26
	0	Idle	----	79.74	----	23.04	----	20.20	----	37.81
	250	5	0.44	18.54	12.15	32.22	1.37	3.64	4.32	11.45
	250	8	0.43	19.30	8.69	24.46	1.14	3.21	2.91	8.16
	250	Idle	----	77.91	----	26.73	----	16.83	----	32.58
	500	3	0.43	16.88	16.64	41.18	1.35	3.34	2.49	6.16
	500	4	0.31	12.52	13.77	34.95	1.61	4.38	3.62	9.19
	500	5	0.30	12.62	12.18	32.31	1.62	4.29	4.93	13.09
	500	6	0.34	14.79	10.35	28.28	1.32	3.61	6.34	17.32
	500	7	0.32	14.42	9.46	26.31	1.35	3.75	4.52	12.58
	500	8	0.33	14.62	8.44	23.71	1.28	3.60	3.24	9.09
EMD	500	1	0.28	8.11	22.11	39.58	1.31	2.34	3.12	5.36
	500	1	----	-----	21.45	38.40	1.45	2.60	2.87	5.13
	500	2	0.28	11.19	15.90	39.93	0.47	1.19	1.46	3.67
	500	2	----	-----	15.41	38.70	0.52	1.32	1.37	3.44
	500	3	0.24	10.13	14.42	37.34	0.42	1.07	1.08	2.80
	500	3	----	-----	14.41	37.33	0.46	1.19	1.04	2.68
	500	4	0.30	12.41	15.08	39.34	0.37	0.97	1.74	4.55
	500	4	----	-----	15.26	39.83	0.41	1.07	1.67	4.36
	500	5	0.37	15.58	14.56	38.32	0.32	0.86	1.69	4.44
	500	5	----	-----	14.38	37.86	0.34	0.90	1.75	4.60
	500	6	0.38	16.04	12.85	34.04	0.32	0.85	2.95	7.80
	500	6	----	-----	12.98	34.38	0.32	0.84	3.20	8.48
	500	7	0.43	18.69	13.00	35.07	0.34	0.91	3.21	8.67
	500	7	----	-----	13.16	35.50	0.37	0.99	3.23	8.72
	500	8	0.26	11.46	12.36	33.73	0.41	1.12	2.22	6.07
	500	8	----	-----	13.33	33.65	0.37	1.00	2.05	5.58
	500	Idle	----	13.05	-----	34.57	----	5.59	----	15.24
	500	Idle	----	-----	-----	34.44	----	5.78	----	15.88

Source: Southwest Research (1987) special analysis.

TABLE A-2. CACLCULATION OF CYCLE-AVERAGE EMISSIONS FOR THE SWRI LOCOMOTIVE ENGINE TESTS

	OPER.		FUEL RATE		EMISSIONS (LB/1000 GAL)				% DUTY CYCLE			FUEL USED IN MODE/HR (GAL)			NOx EMISSIONS IN MODE/HR (LB)			HC EMISSIONS IN MODE/HR (LB)			CO EMISSIONS IN MODE/HR (LB)			PM EMISSIONS IN MODE/HR (LB)		
ENGINE	HOURS	NOTCH	(lb/hr)	(gal/hr	NOx	HC	CO	PM	LINE	SWITCH	AVG.	LINE	SWITCH	AVG.	LINE	SWITCH	AVG.	LINE	SWITCH	AVG.	LINE	SWITCH	AVG.	LINE	SWITCH	AVG.
GE	0	1	51.7	7.3	580.1	83.0	158.7	87.0	4.8	9.6	7.76	0.35	0.70	0.57	0.20	0.41	0.33	0.03	0.06	0.05	0.06	0.11	0.09	0.03	0.06	0.05
	0	2	104.8	14.9	698.2	70.3	82.7	41.8	2.4	4.8	3.88	0.36	0.71	0.58	0.25	0.50	0.40	0.03	0.05	0.04	0.03	0.06	0.05	0.02	0.03	0.02
	500	3	205.2	29.1	638.7	51.8	96.5	18.9	1.9	3.8	3.10	0.55	1.12	0.90	0.36	0.71	0.58	0.03	0.06	0.05	0.05	0.11	0.09	0.01	0.02	0.02
	500	4	320.4	45.6	542.1	63.3	142.5	12.5	4.8	1.9	3.01	2.18	0.87	1.37	1.18	0.47	0.74	0.14	0.06	0.09	0.31	0.12	0.20	0.03	0.01	0.02
	500	5	454.9	64.8	501.1	66.5	203.0	12.6	1.9	1.0	1.32	1.24	0.65	0.86	0.62	0.31	0.43	0.08	0.04	0.06	0.25	0.13	0.17	0.02	0.01	0.01
	500	6	590.2	83.9	436.8	56.0	266.6	14.8	1.9	1.0	1.32	1.61	0.84	1.11	0.70	0.36	0.48	0.09	0.04	0.06	0.43	0.22	0.30	0.02	0.01	0.02
	500	7	697.2	99.0	403.1	58.2	195.1	14.4	2.4	0.0	0.92	2.38	0.00	0.91	0.96	0.00	0.37	0.14	0.00	0.05	0.47	0.00	0.18	0.03	0.00	0.01
	500	8	862.1	122.4	367.7	55.8	141.0	14.6	20.1	0.0	7.65	24.64	0.00	9.37	9.06	0.00	3.44	1.38	0.00	0.52	3.47	0.00	1.32	0.36	0.00	0.14
	250	IDLE		4.0	414.8	261.0	505.3	77.9	23.3	33.2	29.44	0.93	1.33	1.18	0.39	0.55	0.49	0.24	0.35	0.31	0.47	0.67	0.60	0.07	0.10	0.09
	500	BRAKE	98.0	13.9	542.1	63.3	142.5	12.5	3.8	0.0	1.46	0.53	0.00	0.20	0.29	0.00	0.11	0.03	0.00	0.01	0.08	0.00	0.03	0.01	0.00	0.00
		OFF	0.0	0.0	0.0	0.0	0.0	0.0	32.8	44.8	40.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EMISSIONS, LB/HR									100.0	100.0	100.0	34.8	6.2	17.0	14.0	3.3	7.4	2.2	0.7	1.2	5.6	1.4	3.0	0.6	0.2	0.4
EMISSIONS, LB/1000 GAL															403	537	433	63	108	73	162	229	177	17	40	22
EMD	500	1	55.7	7.9	604.7	38.3	83.1	8.1	4.8	9.6	7.76	0.38	0.76	0.61	0.23	0.46	0.37	0.01	0.03	0.02	0.03	0.06	0.05	0.00	0.01	0.00
	500	2	163.0	23.1	609.9	19.5	55.2	11.2	2.4	4.8	3.88	0.55	1.11	0.90	0.34	0.68	0.55	0.01	0.02	0.02	0.03	0.06	0.05	0.01	0.01	0.01
	500	3	227.3	32.3	579.0	17.5	42.5	10.1	1.9	3.8	3.10	0.62	1.24	1.00	0.36	0.72	0.58	0.01	0.02	0.02	0.03	0.05	0.04	0.01	0.01	0.01
	500	4	331.4	47.1	614.0	15.8	80.2	12.4	4.8	1.9	3.01	2.26	0.90	1.42	1.38	0.55	0.87	0.04	0.01	0.02	0.18	0.08	0.10	0.03	0.01	0.02
	500	5	410.4	58.3	590.8	13.8	70.1	15.8	1.9	1.0	1.32	1.12	0.58	0.77	0.66	0.33	0.46	0.02	0.01	0.01	0.08	0.04	0.05	0.02	0.01	0.01
	500	6	554.0	78.7	530.8	13.0	128.3	16.0	1.9	1.0	1.32	1.51	0.79	1.04	0.80	0.40	0.55	0.02	0.01	0.01	0.19	0.10	0.13	0.02	0.01	0.02
	500	7	749.0	106.4	547.3	14.7	134.9	18.7	2.4	0.0	0.92	2.57	0.00	0.98	1.41	0.00	0.53	0.04	0.00	0.01	0.35	0.00	0.13	0.05	0.00	0.02
	500	8	889.0	126.2	522.5	16.4	90.4	11.5	20.1	0.0	7.65	25.41	0.00	9.65	13.28	0.00	5.05	0.42	0.00	0.16	2.30	0.00	0.87	0.29	0.00	0.11
	500	IDLE		4.0	527.3	88.3	241.3	13.1	23.3	33.2	29.44	0.93	1.33	1.18	0.49	0.70	0.62	0.08	0.12	0.10	0.22	0.32	0.28	0.01	0.02	0.02
	500	BRAKE	98.0	13.9	614.0	15.8	80.2	12.4	3.8	0.0	1.46	0.53	0.00	0.20	0.33	0.00	0.12	0.01	0.00	0.00	0.04	0.00	0.01	0.01	0.00	0.00
		OFF	0.0	0.0	0.0	0.0	0.0	0.0	32.8	44.8	40.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
									100.0	100.0	100.0	35.9	6.6	17.8	19.3	3.8	9.7	0.7	0.2	0.4	3.4	0.7	1.7	0.4	0.1	0.2
															537	577	546	18	33	22	95	104	97	12	12	12

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